

# **Technology Final Report**

## **Non-ODC Oxygen Line Cleaning for use on DOD Weapons Systems**

**OC-ALC/LGERC**

**October 10, 2003**



Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>10 OCT 2003</b>		2. REPORT TYPE <b>Final</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Non-ODC Oxygen Line Cleaning for use on DOD Weapons Systems</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>Ms. Mary Hayes</b>				5d. PROJECT NUMBER <b>PP 9910</b>	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Air Force Room C-109 4375 Chidlaw Road Wright-Patterson AFB, OH 45433-5006</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>Environmental Security Technology Certification Program 901 N Stuart Street, Suite 303 Arlington, VA 22203</b>				10. SPONSOR/MONITOR'S ACRONYM(S) <b>ESTCP</b>	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>The original document contains color images.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>SAR</b>	18. NUMBER OF PAGES <b>100</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

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**TO:** Director, Freedom of Information & Security Review, Rm. 2C757, Pentagon

## 1. DOCUMENT DESCRIPTION

a. TYPE Final Report	b. TITLE Non-ODC Oxygen Line Cleaning for use on DoD Weapons Systems (PP-9910)
c. PAGE COUNT 99	d. SUBJECT AREA Environmental Security Technology Certification Program (ESTCP)

## 2. AUTHOR/SPEAKER

a. NAME (Last, First, Middle Initial) Hayes, Mary	b. RANK	c. TITLE
d. OFFICE OC-ALC/LGERC	e. AGENCY Air Force	

## 3. PRESENTATION/PUBLICATION DATA (Date, Place, Event)

Posting on the ESTCP web site.

**CLEARED**  
For Open Publication

JUL 12 2005 3

Office of Freedom of Information  
and Security Review  
Department of Defense

## 4. POINT OF CONTACT

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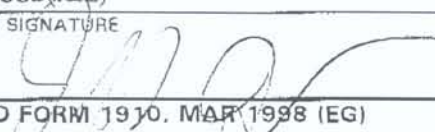
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e. OFFICE OUSD(I&E)	f. AGENCY OUSD (A&T)
g. SIGNATURE 	h. DATE SIGNED (YYYYMMDD) 20050706

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# **Non-ODC Oxygen Line Cleaning for use with DOD Weapons Systems**

**OC-ALC/LGERC**

**16 September 2002  
Revised 11 June 2003  
Revised 10 October 2003**

## **Acknowledgements**

This final report was originally prepared by Versar, Inc. and was rewritten by Concurrent Technologies Corporation (CTC) to satisfy the requirements of the Environmental Security Technology Certification Program (ESTCP), Project No. PP-199910. This report was prepared on behalf of, and under guidance provided by, the United States Air Force (USAF), ESTCP, Tinker Air Force Base, and the Joint Group for Pollution Prevention (JG-PP). The structure, format and depth of the report were determined by the ESTCP in response to the specific needs of this project.

The project team wishes to thank the participants involved in the creation of this document for their invaluable contributions: the ESTCP, the JG-PP, Tinker Air Force Base (AFB), Robins AFB, the Oklahoma Air National Guard (ANG), Tulsa ANG Base, and the B-1B, B-2, F-15, and F-16 aircraft programs.

The Technology Final Report and Joint Test Report (JTR) document the results of testing performed in accordance with the *Joint Test Protocol (J-99-CL-015-P1) for Validation of Alternatives to Ozone-Depleting Chemicals Used in Oxygen-Line Cleaning*, dated July 24, 2001. These reports are available as a reference for future pollution prevention endeavors by other U.S. Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and industry organizations to minimize duplication of effort.

## Executive Summary

This project successfully addressed both an environmental issue and a key technology issue related to military aerospace vehicles. Through this project, government and industry joined to develop a better way to clean the oxygen-supply systems of weapons systems by replacing ozone-depleting chemicals and a labor-intensive process with an environmentally safe, automated method that greatly improves upon past practices. The new technology developed as a result of this project improves the readiness of military aircraft, reduces costs, and dramatically reduces the crewmembers' chances of exposure to unhealthy toxins.

Weapons systems have several types of oxygen-supply systems, all of which eventually develop contamination in the distribution systems as a result of opening the lines for maintenance. Contaminants and particulates within oxygen systems can pose significant hazards to both personnel and aerospace vehicles.

Typical onboard oxygen-line contaminants include Zeolite, dirt or dust particles, and non-volatile residue (NVR) substances in unknown quantities. Zeolite presence is enough to leave the faces of crewmembers white from the dusting. It is impossible to determine the extent to which crewmembers inhale the Zeolite dust. In addition to these human concerns, contaminant buildup decreases system performance, increases demand on maintenance resources, and prematurely removes the aircraft from mission support.

Currently, when contamination occurs, pilots must switch to the use of auxiliary oxygen supplies. The aircraft is flown to an air base where the oxygen plumbing is completely dismantled, removed from the aircraft, cleaned using chlorofluorocarbons (CFCs), and then reinstalled in the aircraft. This time-consuming process is neither cost-effective nor safe. CFCs used in the cleaning process (such as CFC-113 and HCFC-141b) have superior cleaning ability, low-vapor pressure, and low flammability; however, these chemicals have been identified as ozone-depleting substances. As a result of international agreements and the Clean Air Act Amendments of 1990, use of these ozone-depleting chemicals must be phased-out. In fact, the Clean Air Act stipulated that U.S. military forces discontinue using all ozone-depleting materials by 2000.

The Environmental Security Technology Certification Program (ESTCP), a program of the U.S. Department of Defense (DoD), demonstrates and validates proven technologies that target the DoD's most urgent environmental needs. The ESTCP sponsored the project, "Onboard Oxygen-Line Cleaning System for Use with DoD Weapons Systems," to design, construct and demonstrate/validate an environmentally friendly prototype oxygen-line cleaning system (OLCS). In addition to the ESTCP, the project team included the U.S. Air Force; the Joint Group on Pollution Prevention (JG-PP); Tinker Air Force Base (AFB); Robins AFB; the Oklahoma Air National Guard (ANG); Tulsa ANG Base; the B-1B, B-2, F-15, and F-16 aircraft programs; Versar, Inc.; and Concurrent Technologies Corporation (CTC).

The Oxygen Line Cleaning System (OLCS) was developed at Versar, Inc. in Oklahoma City, OK, an industrial complex located near Tinker AFB. To test the OLCS, a full-scale replica of the B1-B oxygen system had to be constructed because of the potential risks involved with cleaning an actual B1-B aircraft. Using the B1-B replica, experimental testing verified that the OLCS could successfully clean all areas within the oxygen lines. Next, an actual B1-B aircraft was cleaned. Finally, the OLCS was tested on the F-16 at Tulsa Air National Guard Base and on the F-15 at Robins AFB.

Performance objectives of this project included cleanliness verification, functionality and operability of the OLCS.

To meet the functionality objective, the unit was designed to be fully transportable, self sufficient and easily moveable. Functional testing indicated no problems associated with the use of the HFE-7100 solvent when used with the OLCS. Government representatives observed and approved the use of this equipment on the B-1B, F-15, F-16, and the C-130 aircraft. Dead-area testing indicated that the dry air purge of the system must be used in conjunction with the vacuum purge to assure that no HFE-7100 remains in the aircraft after the cleaning procedure. The leak testing conducted as part of the OLCS procedure is a high-pressure test for determining the potential loss of solvent in the aircraft. Test results from the modified procedure indicated that the system passed the high-pressure test and that the solvent did not present a hazard during use.

Most of the tests listed in the JTP were conducted as specified in the JTP. In executing some of the tests, deviations from the required procedure became necessary to accomplish the intended goal. These deviations were fully agreed upon by all stakeholders and are detailed in Section 2.1.2 of the JTR. The test results indicated that the OLCS would meet the performance requirements for cleaning oxygen-line systems in aerospace vehicles. Information contained in this report is presented to enable potential users to decide if the test results are applicable for their specific needs.

Cleanliness was verified through the use of a particle counter. When using the B-1B mock-up, researchers tested the particle count using a metal coupon cut from the oxygen line. The metal coupon was marked to ensure comparison region of interest, cleaned, weighed, photographed to verify the existence of any contaminants, contaminated, re-weighed, then photographed again. The procedure was then repeated to verify that the coupon was cleaned. Demonstrations performed on actual aircraft involved laboratory analysis of contaminants captured in the filter of the OLCS. Laboratory analysis consisted of visible-light microscopy, Infrared (FT-IR), X-Ray spectroscopy and Fluorescence spectroscopy, as appropriate. Laboratory tests were qualitative; quantification was not considered feasible.

Operability was based on user friendliness through the use of a touch-screen monitor. The unit has a working touch-screen monitor and can be operated by one individual rather than a team of people using solvents and rags.

The new Oxygen-Line Cleaning System (OLCS) is contained within a 12' x 7' trailer that can easily be maneuvered alongside an aircraft. It successfully replaces the use of ozone-depleting solvents, rags and elbow grease, fully automating the way contaminated oxygen systems are cleaned.

Using this new technology, one operator can clean the entire plumbing system on an aircraft the size of a B1-B in less than four hours at an estimated cost of less than \$2,500. Because lines on a contaminated B1-B aircraft are removed and cleaned off-equipment in a process that requires more than 15 gallons of CFC-113, the current cost could be in excess of \$1 million. Each time the OLCS is used on a B1-B, the Air Force eliminates the need to dispose of more than 15 gallons of hazardous waste. This cost data is high-level, preliminary and is based on limited analysis. In order to fully validate this system for implementation, a more rigorous cost-saving methodology is required such as could be provided by the JG-PP Cost Benefit Analysis approach.

Technology transfer activities are already underway both in government and the commercial sector. For example, this technology can be applied to cleaning any type of plumbing system, including hydraulic and fuel systems. The gas industry has expressed interest in cleaning medical-oxygen systems installed in hospitals and medical offices. NASA has expressed interest in cleaning oxygen lines in rocket-engine cells. WR-ALC is having the concept adapted to clean gaseous oxygen carts.

The OLCS reduces environmental risks, assists the U.S. Military in Clean Air Act compliance, and enhances aircraft readiness. This report, in conjunction with the Joint Test Report (JTR), summarizes the demonstrations and findings of the ESTCP Project PP-199910, Non-ODS Oxygen-Line Cleaning for Use on DoD Weapons Systems.

# **1. Introduction**

## **1.1. Background Information**

Depletion of the ozone layer in the upper atmosphere increases the intensity of harmful radiation reaching the earth's surface. For this reason, chemicals with known ozone-depleting potential (ODP) are being phased out of industrial and commercial use. Although some waivers are in place allowing chlorofluorocarbon (CFC) use, the Montreal Protocol and several Executive Orders (such as 12856 and 13149) have tasked government agencies to identify cleaning solvents to replace CFC-113.

CFC-113 solvents such as Freon have high ODP, yet are commonly used to clean the oxygen-supply systems of DoD aircraft. The goal of this project is to develop an environmentally friendly and cost-effective method of cleaning the oxygen-distribution lines and storage systems in military aerospace vehicles, eliminating or reducing the use of CFC-113 solvents.

Tinker Air Force Base (AFB), OK, in conjunction with Environmental Security Technology Certification Program (ESTCP) and the Joint Group for Pollution Prevention (JG-PP), coordinated efforts with Versar, Inc. to identify a suitable solvent system that can eliminate the specific pollution issues associated with CFC-113.

Weapons systems have several types of oxygen-supply systems, all of which eventually develop contamination in the distribution system. Oxygen lines on military aircraft consist of tubes that are connected between a Liquid Oxygen (LOX) converter, oxygen cylinder or Molecular Sieve Oxygen Generating (MSOG) system and an oxygen regulator. The oxygen regulator is connected to the oxygen masks of the crew. Many oxygen-system components (i.e. pressure transducers, pressure relief valves, check valves, toggle switches, etc.) are placed strategically between the LOX converter, cylinder or MSOG unit and the masks. Contaminant buildup within these oxygen-system components decreases system performance, increases demand on maintenance resources and prematurely removes the aircraft from mission support. This project addresses three specific objectives relating to the oxygen-system cleaning process.

One objective of the project was to identify materials (metals, elastomers and plastics) used within the oxygen-system components and find the solvent that is most compatible to these materials while still allowing an acceptable level of cleaning.

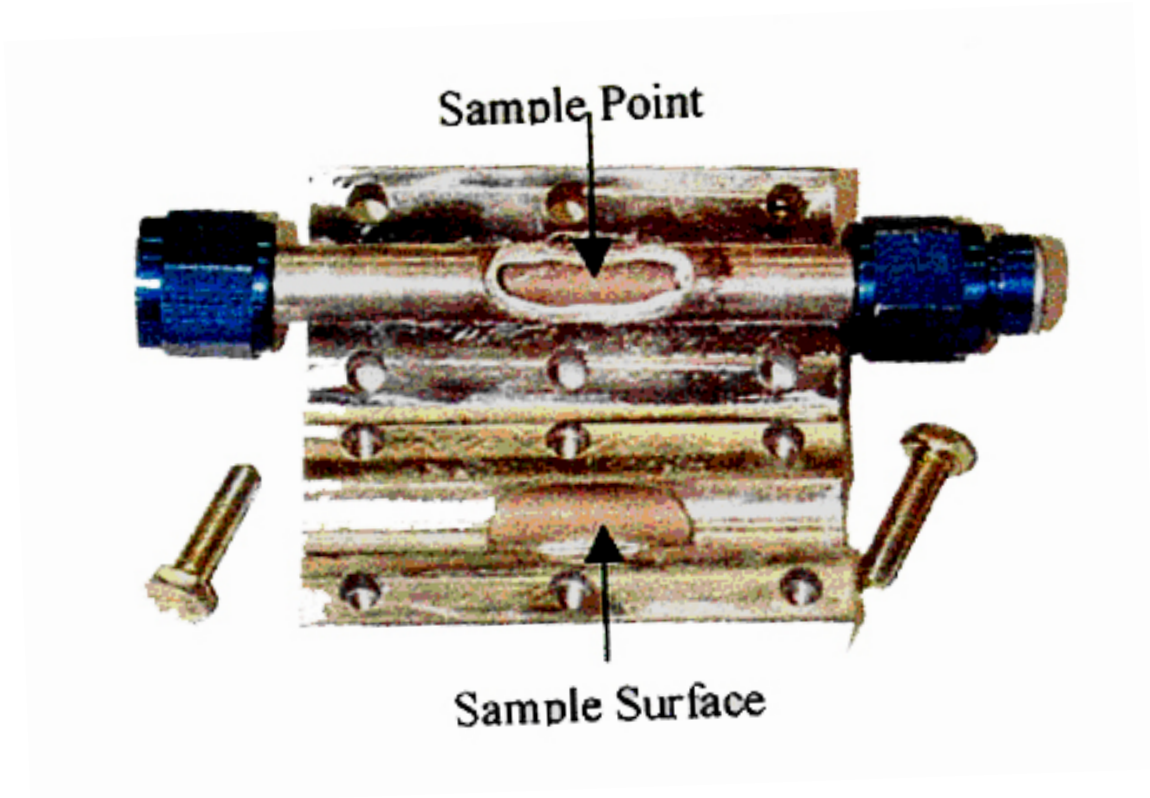
A second objective was to design, develop, and construct an OLCS flexible enough to meet the cleaning requirements of all oxygen-line systems (smallest to the largest).

A third objective was to create a system that would successfully clean oxygen lines without having to remove the lines from the aircraft. Disinfecting the entire oxygen system without having to disassemble the entire aircraft oxygen plumbing system will save considerable time and money.

The B1-B aircraft was chosen for establishing a design basis for a prototype OLCS (OLCS). A full-scale replica of the B1-B oxygen system had to be constructed because of the potential risks involved with cleaning an actual B1-B aircraft. Using the B1-B replica, experimental testing verified that the OLCS could successfully clean all areas within the oxygen lines. Next, an actual B1-B aircraft was cleaned.

In addition to cleaning, the replica B1-B system was used to determine whether the previous test data for flow velocity and fluid composition was accurate and reproducible. This was to establish whether the system was capable of effectively removing contaminants that have the strongest adhesion to the surface of the lines. Test cells such as the one pictured in Figure 1 were designed and constructed to visually qualify the cleaning ability of the solvent/surfactant solution.

The expected benefit of the new OLCS technology is to reduce or eliminate the dependence on ODCs used to clean aircraft-oxygen systems and equipment, resulting in environmental improvements. Successful completion of this program will also reduce aircraft downtime and decrease the time and expense currently associated with maintaining oxygen systems. In addition, both the DoD and commercial aircraft carriers should save money by eliminating the need to purchase and dispose of ODC chemicals. Finally, the process is expected to be adaptable to other critical equipment and systems providing additional cost and environmental savings.



**Figure 1: Test Cell Assembly**

### **1.2. Official DoD Requirement Statement(s)**

The DoD requirements for this project are to design, develop, test, and demonstrate a prototype machine capable of cleaning the oxygen-line system of various aerospace vehicles (onboard) with environmentally acceptable chemicals.

### **1.3. Objectives of the Demonstration**

The objective was to demonstrate the full capability of the OLCS by cleaning the oxygen lines of a B-1B aircraft at Tinker AFB, OK. The successful demonstration validated the oxygen-line cleaning prototype, proved its environmental acceptability, validated the discovery of a cost-effective alternative to CFC-113 (Freon), and proved that the OLCS is a cost-effective method for onboard cleaning of aircraft oxygen systems.

The original scope of the project was to demonstrate cleaning a B-1B aircraft at Tinker AFB, OK. After partnering with the Joint Group on Pollution Prevention (JG-PP), the scope was expanded to include demonstration cleaning on the F-16 and F-15 aircraft, with possible participation from NASA. Because NASA was unable to secure funding, they did not participate in any field demonstrations. In order to attain access to the three aircraft types, demonstrations

were expanded to three locations. The initial demonstration was conducted at Tinker AFB, OK, for the B-1B aircraft. The F-16 demonstration took place at the Tulsa Air National Guard Base, Tulsa OK, and the F-15 demonstration was held at Robins AFB, GA.

In order to institute a process change, the new validated cleaning process is being added to Technical Order 15X-1-1, Maintenance Instruction - Oxygen Equipment, the governing general technical order for maintaining oxygen equipment. This process change to the technical order will then give Air Force program offices the option of implementing the OLCS technology. Each weapons system program office is autonomous in its decision to implement new technologies on a specific weapons system.

The project team contacted all weapons system program managers regarding possible implementation of this technology. Each weapons system program office is responsible for generating new cleaning requirements and listing new alternate cleaning methods certified for use on a particular weapons system. This is done through Air Force technical order changes for each individual weapons system.

The results of this project have been disseminated to government and industry. For example, information regarding the new oxygen-line cleaning system has been published in *AFMC Monitor Magazine*. Presentations have been made to the Pollution Prevention Conference and to the Oxygen Standardization Coordination Group to assist Military Services, Original Equipment Manufacturers (OEMs) and the FAA in determining applicability to their processes. Several OEMs are using this technology and are identified in Appendix B, Contacts. The new oxygen-line cleaning system could become a requirement for delivery of new aerospace vehicles.

#### **1.4. Regulatory Issue**

A Congressional Mandate has banned the regular use of all chlorofluorocarbons (CFCs) and other volatile ozone-depleting compounds. The Clean Air Act, along with the Congressional Mandate and international agreements, prohibited the use of all ozone depleting materials by the United States military forces by 2000. As noted in section 1.1, there are some waivers in place allowing the use of CFC-113, but the DoD stockpiles are dwindling, and the quality of the stock is falling below acceptable standards.

#### **1.5. Stakeholder/End-User Issues**

Several issues do exist and are explained fully in Section 8.0 of this report.

#### **1.6. Previous Testing of the Technology**

The original effort to study the capability of cleaning an entire oxygen system began in 1995. A contract was awarded to Northwest Pacific Labs to determine if a suitable, environmentally friendly chemical was available that could adequately clean oxygen-system components. HFE-

7100, methoxy-nonafluorobutane ( $C_4F_9OHC_3$ ) was determined to be a suitable solvent. The next step was to develop a bench-top system that could clean an entire aircraft system. Contracts were awarded to ARINC Inc., SSAI, and Surfactant Associates to develop a bench-top prototype system capable of testing and reproducing test data. Once the bench-top system was demonstrated, work began to develop a system to clean aircraft oxygen converters, a simple and logical starting point in cleaning the entire oxygen system.

A prototype converter cleaner was built and operational by 1997, and the technology and experience gained from this system was utilized to develop the current oxygen-line cleaning system. Additionally, as the OLCS was developed, modified, and optimized, knowledge gained in its development was utilized in modifying and enhancing the original converter cleaning system.

## **2. Technology Description**

### **2.1. Description**

The OLCS is contained within a 12' x 7' trailer that can easily be maneuvered alongside an aircraft. See Figures 2 and 3 for photos of the prototype. This new technology provides an environmentally friendly method of cleaning an onboard oxygen plumbing system without having to remove equipment from the aircraft. The OLCS connects to the aircraft at the oxygen storage-vessel point, with a return line connected at the crewmember's oxygen regulator location. Solvent is then pumped through the existing onboard plumbing system and returned back to the OLCS for analysis, filtration, and eventual distillation for reuse. The complete cleaning cycle leak-tests, washes, rinses, analyzes, evacuates, dry-air purges, and distills the cleaning chemicals.

The original concept was to utilize a solvent/surfactant mixture to clean the onboard oxygen plumbing system. Developmental testing validated that cleaning with solvent alone (HFE-7100, methoxy-nonafluorobutane,  $C_4F_9OHC_3$ ) at a specified fluid flow rate cleaned as well as a solvent/surfactant mixture, HFE-7100/Krytox alcohol. As a result, surfactant was omitted from the process, which decreased the complexity of the system while making it inherently safer.

The cleaning process begins by connecting the lines on the OLCS to oxygen lines onboard the aircraft. The oxygen lines are pressurized with dry air to ensure that no significant leaks are present in the system. Leaks must be located and eliminated before the cleaning process begins. When leaks are maintained to acceptable guideline limits (established in the Versar Test Plan at 0.50 inches of mercury pressure), a vacuum is applied to the aircraft. This will insure that the solvent removal process will not be hindered. Solvent is then pumped and circulated through the oxygen lines. A filter is set up in the circulation loop to remove any particulate matter from the system. This process continues until each segment of aircraft tubing is cleaned for 5-10 minutes at a specified minimum-flow rate to obtain adequate contaminant removal. A rinse cycle removes any remaining contaminants from the oxygen lines. A sample from the rinse-cycle

effluent stream is analyzed with an in-line particle counter to evaluate cleanliness. If the appropriate cleanliness level has not been achieved, the computer will initiate a series of steps to re-wash the lines.

If the oxygen lines meet the cleaning criteria, an air purge is initiated to push as much liquid out of the plumbing system as possible. Once the air purge is complete, a vacuum is applied to the oxygen line to vaporize the remaining solvent. The computer monitors the system pressure until it has dropped below 0.25 psia. Experiments have shown that no visible quantities of solvent remain in the system below this pressure. The computer maintains the pressure below 0.25 psia for five minutes before initiating the air-purge cycle for approximately 45 minutes, depending upon system volume. The air is allowed to enter a halogen detector to detect the presence of solvent in the lines. If the solvent (halogen) level is above 40 parts per million, the air is passed through the system for another 30 minutes, then re-evaluated. When the solvent level is below 40 parts per million, the cleaning process is complete.

The LabView software program allows the operator to view (on the touch-screen monitor) the cleaning cycles, the cycle time, and the cleanliness levels. If any problems occur during the process, the operator is alerted and guided (on screen) as to how to correct the problem. When the oxygen lines have been cleaned to an acceptable level, the program starts the distillation cycle to purify the solvent.

One operator can carry out this entire cleaning process in less than four hours for an aircraft the size of the B1-B. It is estimated that the oxygen lines on a B-1B aircraft can be cleaned for less than \$2500.00. Because lines on a contaminated B-1B aircraft are removed and cleaned off the aircraft, the current cost could be in excess of \$1,000,000. A longer cleaning time is required for larger aircraft with more outlets. A manifold must be constructed specifically for the number of outlets on the aircraft being cleaned to regulate the velocity of the cleaning fluid. A CD-ROM containing software-programming information will be provided for each individual aircraft type that has been validated. Each aircraft type will require validation and CD development. The CD will control the entire cleaning process to include flow velocities and distribution of the correct amount of solvent to the appropriate tanks.

Application of this technology can be expanded; any type of plumbing system can be cleaned using the OLCS, including hydraulic and fuel systems. Another possible alternative is use in commercial applications. The gas industry has expressed interest in using this new technology to clean medical-oxygen systems installed in hospitals and medical offices. NASA has expressed interest in cleaning oxygen lines in rocket engine test cells. WR-ALC is having the OLCS concept adapted to clean gaseous oxygen carts.



**Figure 2: OLCS Top View**



**Figure 3: OLCS RH Side View**



## **2.2. Strengths, Advantages, and Weaknesses**

The new process is an environmentally friendly method of cleaning with the advantage of utilizing a closed-loop system that minimizes the loss of solvent. Safer chemicals are used, and lower emissions result from a self-contained re-purification process onboard the unit.

Strengths of this new technology are as follows:

- Aircraft oxygen equipment remains clean and is not re-contaminated as a result of unpacking and re-assembly.
- There are significant cost reductions in cleaning a contaminated oxygen system.
- The cleaning is verifiable by a defined process that did not exist with previous cleaning techniques.

Advantages of this new technology are as follows:

- The system is a fully automated process.
- The system cleans better than previous cleaning processes.
- The system enhances the readiness of the military aerospace fleet.

Disadvantages of this new technology are as follows:

- There is an initial cost for equipment and solvent.
- This prototype was developed for demonstration on any aircraft system in the inventory, therefore the size of the unit is large.
- Because the technology is new and replaces the practice of using solvent and rags, technicians and operators must be trained in its use.

## **2.3. Factors Influencing Cost and Performance**

Various factors influenced the cost and performance of the OLCS. These factors are as follows:

- Experimentation was required in order to identify proper equipment to achieve the desired results.
- The sophistication and size of the unit allows for an expanded range of operation; therefore, there is a significant reduction in operational cost.
- To achieve optimum cleaning results, larger pumps and plumbing were required to provide flow rates of 15 to 22 fps. Earlier testing done by previous contractors stated that 3 to 5 fps would clean any contamination for the oxygen lines. The current contractor could not duplicate these results; therefore, additional testing was required prior to construction of the system
- The use of sophisticated verification equipment was required to verify cleanliness capability of the system.

Maintenance requirements for the system are as follows:

- Routine trailer maintenance
- Filter element changes
- Fluid replenishment
- Sensor calibrations
- Distillation sludge disposal (dependant upon frequency of use)
- Maintenance repair of the system, as required.

### **3. Site/Facility Description**

#### **3.1. Background**

The OLCS was developed at the Versar office, shop and laboratory in Oklahoma City, OK., an industrial complex just south of Tinker AFB. The shop provided ample room to construct the OLCS trailer and equipment. Government-furnished equipment allowed for the construction of a full-scale mock-up of a B-1B oxygen system, which was used for initial validation testing of the OLCS. This is the same site where the oxygen converter cleaning system was constructed (the predecessor to the OLCS). All testing was conducted in the facility to verify that the cleaning system functioned and performed as designed prior to actual connection to an operational aircraft.

Because the OLCS had to be field tested on selected weapons systems, site-selection criteria for field demonstrations were previously identified in the JTP. Three separate test sites were required since the B-1B, F-15, and F-16 weapons-systems aircraft are not based together.

The initial test site for the B-1B was Tinker AFB, OK, since the OLCS was initiated for use on this aircraft. Tinker AFB is the major overhaul depot for the B-1B and home to the B-1B program office.

The second test site—Tulsa Air National Guard Base in Tulsa, OK—houses the F-16 aircraft. Working with the F-16 program office it was decided that this was the preferred test location due to its proximity with Oklahoma City and because it was the closest location with F-16s. The one negative impact of this location was that it was not the depot for the F-16; however, F-16 program office personnel attended the demonstration in order to fully understand the cleaning process.

The third site for the F-15 aircraft was at Robins AFB, GA. Robins AFB is the major depot for the F-15 and home to the F-15 program office. Certain requirements needed to be adhered to for the testing of the aircraft. The equipment needed to be positioned inside a maintenance hangar at an Air Force base with an electrical power supply of 208 volt, 40 amp, and 3-phase electricity.

This infrastructure would be similar in all test locations and would be able to accommodate multiple weapons systems at that location.

Additionally, as part of another program, the OLCS was demonstrated on a C-130 aircraft at the Air National Guard base in Louisville, KY.

## 4. Demonstration Approach

### 4.1. Performance Objectives

The objective of this project was to produce a system that would clean to accepted industry standards. The performance objectives included cleanliness verification, functionality and operability of the OLCS. Cleanliness is determined through the use of a particle counter. Functionality is based on a fully transportable, self sufficient and easily moveable unit. This unit will complete all phases of a cleaning operation to include purging, testing for cleanliness, and checking for leaks. Operability is based on user friendliness through use of a touch-screen monitor. This will enable the operator to start the system with the touch of an icon on the screen and operate the system without constant monitoring. Through test runs and optimization, the unit is programmed to complete the cleaning cycle in a timely and efficient manner.

This section of the report will summarize the results of the testing performed on the OLCS to demonstrate that the performed objectives were met. Table 1 below lists the performance objectives and the specific tests that were performed.

**Table 1 Cleanliness Verification Table**

#### 4.1.1 Liquid Oxygen (LOX) Compatibility Performance Objectives Test

	Cleanliness Verification	Functional	Operability
LOX Compatibility Test	N/A	PASS Section 4.1.1, Table 12, Final Report	N/A
Materials Compatibility Test	N/A	PASS Section 2.1.2.2, Table 33, JTR	N/A
Nonvolatile Residue Test	PASS Section 4.1.3, Table 14, JTR	N/A	N/A
Moisture Test	N/A	PASS Section 4.1.4, Table 14, JTR	N/A
Dead Area Test	PASS Section 4.1.8, Figure 2, JTR	N/A	N/A
Leak Test	N/A	PASS Section 4.1.9, Figure 4, JTR	N/A
Hazards Analysis Test	N/A	PASS Section 4.1.10, JTR	N/A
Functional Test	N/A	PASS Section 4.1.6, JTR	N/A
Component Test	PASS Section 4.1.7 and Appendix F, JTR	N/A	N/A

The LOX compatibility test (LOX Impact Test) was the first test initiated because the functionality of the OLCS depended on identifying a base solvent mixture that was non-explosive in an oxygen-rich environment. Until HFE-7100 was identified as the preferred solvent through LOX compatibility testing, the project could not have proceeded.

Initial LOX testing demonstrated that Krytox Alcohol/HFE-7100 mixture for onboard oxygen-line cleaning would not pass the LOX compatibility test. Further testing showed that a high-flow velocity of neat HFE-7100 was capable of precision cleaning without the use of Krytox Alcohol. This was a more preferred method for the OLCS because it simplified the cleaning process since surfactant mixing and verification of removal are not required.

#### **4.1.2 Materials Compatibility with Cleaning Solvent Surfactant Mixture Test**

One series of tests conducted to meet the functionality objective was the materials compatibility test, which was necessary to determine if the cleaning process would damage any aircraft or system component.

The original list of materials that were tested can be found in Section 2.2 and Table 3 of the JTP. This list consists of various materials that may come into contact with the cleaning solution during the line-cleaning process. Results of the materials compatibility test are in Table 13 of the JTR.

The JTP also required that a Gas Chromatograph (GC) be used to analyze the cleaning solution samples used to soak the tested materials. As Section 2.1.2.2 of the JTR explains, the use of GC results are not required according to the ASTM G-127. After review of the initial GC results and discussions with chemists at OC-ALC, it was determined that GC testing for compatibility is of limited value.

#### **4.1.3 Nonvolatile Residue Test**

To verify cleanliness, one of the performance objectives, researchers conducted nonvolatile residue testing. The purpose of the nonvolatile residue tests was to provide a qualitative determination of how well the oxygen lines were cleaned; the test compared the nonvolatile residue present before and after cleaning.

The nonvolatile residue testing method confirmed removal by accounting for all nonvolatile residue in the cleaning solution and the filters.

The original test procedure was designed from a bench-scale test. The procedure had to be modified due to the design and size of the OLCS; however, the modified procedure accomplished the intended goal of providing a qualitative determination that the oxygen lines

were adequately cleaned. Results from the nonvolatile residue test are found in Table 14 of the JTR.

#### **4.1.4 Moisture Test**

This test related to the functionality performance objective of the project. It was necessary to perform this test and measure moisture within the OLCS because moisture is a very serious danger in the oxygen distribution tubing of an aircraft. This moisture may freeze at high altitudes and cause essential valves and sensors to malfunction. Therefore, it is essential to check the solvent drum for moisture.

The moisture test showed that the AFE-71W solvent used in the OLCS met and exceeded the specified acceptance criteria. Results are given in Table 15 of the JTP. The solvent had moisture content of 8 ppm and 7 ppm; 60 ppm of water had been deemed acceptable.

#### **4.1.5 Dead Areas Test**

Dead-areas testing was requested in the JTP to help satisfy the cleanliness performance objective. The tests measured the redeposition and removal of all chemicals in dead areas of the aircraft tubing. To complete the test, dead space within the oxygen-line cleaning system was identified, then removed and visually inspected after cleaning. No trace of HFE-7100 was present in the dead-space volume after cleaning. Therefore, the dead-areas test supported the stated performance objective.

#### **4.1.6 Leak Test**

The leak test conducted as part of the OLCS procedure was a high-pressure test for determining the potential loss of solvent in the aircraft. The test was designed to ensure that no significant leaks would be present in the oxygen-line system.

Results from the modified test procedure indicated that the system passed the high-pressure test and that the solvent did not present a hazard during use. These results relate to the functionality performance objective of the project, showing that the OLCS had an acceptable leak rate.

#### **4.1.7 Hazards Analysis Test**

Extensive hazardous analysis testing proved that HFE-7100, the cleaning solvent used in the OLCS, is non-explosive in a pure oxygen environment and is unable to sustain a fire under normal operating conditions. This test, then, answered a key performance objective related to functionality of the OLCS.

This test is required under NASA Technical Memorandum 104823 (Guide for Oxygen Hazards Analysis on Components and Systems, October 1996), and was deemed necessary by the U.S.

Air Force. The focus of the hazardous analysis investigation was to collect information on the components and the worst-case operating conditions. The hazardous analysis investigation, in conjunction with all other tests, proved that HFE-7100 was non-explosive in a pure oxygen environment and was unable to sustain a fire under normal operating conditions.

#### **4.1.8 Additional Test**

##### **4.1.8.1 Functional Test**

The JTP required that no odor be present after cleaning and that the system be fully functional after cleaning. The functional test was conducted to verify that this performance objective could be met. Section 4.1.6 of the JTR reports that this objective was met, noting that "Government representatives breathed through masks for several minutes to test the quality of the oxygen flowing through the lines that were cleaned. No noticeable odors were detected."

##### **4.1.8.2 Component Test**

This test was proposed to verify the capability of the cleaning process. This, the third test directly related to the performance objective of cleanliness verification, resulted in approvals from four individual Air Force Bases, as discussed in Section 4.1.7 of the JTR.

To conduct the component test, lines were cleaned numerous times on the B-1, F-15, F-16 and C-130 aircraft. Air Force personnel then reviewed and approved each test and demonstration.

#### **4.2. Physical Setup and Operation**

A full-scale mock-up of a B-1B oxygen-line system was produced. Testing was initiated on the OLCS by setting up electricity (208v, 3 phase-60 cycle), water, and furnishing clean, dry air from an air compressor that is an integral part of the prototype. In the test phase (proof of concept), certain parts of an oxygen line were contaminated, placed back in the line, cleaned using the prototype system, removed, and inspected using an optical microscope for cleanliness results. In the validation phase, the prototype was attached to an aerospace vehicle oxygen system with only one individual being required to perform the cleaning process. In the prototype, a particle counter and halogen-leak detector insures that the oxygen system has been cleaned to accepted industry and military standards. This prototype uses a closed-system process that automatically recycles and regenerates the fluid for reuse.

#### **4.3. Testing Procedures**

Test procedure for the B-1B mock-up consists of a metal coupon being laser cut from the oxygen line, marked (to insure comparison region of interest), cleaned, weighed, photographed (to verify that there are no contaminants), contaminated, re-weighed, and photographed again. The metal

coupon is then clamped back into the oxygen line, cleaned, removed, re-examined, re-weighed and photographed to verify that the coupon has been cleaned.



**Figure 5: OLCS Cleaning C-130 Oxygen Lines**

#### **4.4. Evaluation Procedures**

To evaluate the cleaning demonstrations performed on actual aircraft, researchers conducted laboratory analyses of any contaminants captured in the filter of the OLCS. Laboratory analysis consisted of visible-light microscopy, Infrared (FT-IR), X-Ray spectroscopy and Fluorescence spectroscopy, as appropriate for individual analysis performed. Laboratory tests were qualitative in nature. Quantification was not considered feasible.

For additional information, see Appendix A of the JTP and Appendix C of the Test Plan and Procedures.

## 5. Performance Assessment

### 5.1. Performance Data

The primary procedure used for testing the validity of the OLCS is contained in the *Joint Test Protocol (J-99-CL-015-P1) for Validation of Alternatives to Ozone Depleting Chemicals in Oxygen Line Cleaning*, dated July 24, 2001. For each project sponsored by the Joint Group on Pollution Prevention, a Joint Test Protocol (JTP) is established which contains the critical requirements and tests necessary to qualify potential processes for a particular application. The complete JTP is available for review at [www.jgpp.com](http://www.jgpp.com). The results of the testing performed in accordance with the JTP, or any deviations thereof, are summarized in a *Joint Test Report (JTR) for Validation of Alternatives to Ozone Depleting Chemicals Used in Oxygen Line Cleaning*, August 15, 2002. The JTR is attached to this report as Appendix A. Any additional test data is available for review in Appendix C.

Cleanliness Verification – These tests were intended to provide the most thorough verification of the cleaning capabilities of the OLCS. The JTP states that this test determines the cleanliness level of a test article by determining particle counts, NVR, and surface particulate verification by using a scanning electron microscope (SEM). However, certain modifications had to be made to this cleanliness verification test.

Visual verification of cleanliness was recorded using digital photos of each test coupon. These photos were taken before contamination, after contamination, and after cleaning. These photos are included in Appendix E of the JTR.

The particle count testing of the effluent stream was another modification that had to be made to the cleanliness verification test. More direct methods of cleanliness verification were developed and used for this test. Test deviations can be reviewed in Section 2.1.2.4 of the JTR.

When using the B-1B mock-up, researchers tested the particle count using a metal coupon cut from the oxygen line. The metal coupon was marked to ensure comparison region of interest, cleaned, weighed, photographed to verify the existence of any contaminants, contaminated, re-weighed, then photographed again. The procedure was then repeated to verify that the coupon was cleaned. Demonstrations performed on actual aircraft involved laboratory analysis of contaminants captured in the filter of the OLCS. Laboratory analysis consisted of visible-light microscopy, Infrared (FT-IR), X-Ray spectroscopy and Fluorescence spectroscopy, as appropriate. Laboratory tests were qualitative; quantification was not considered feasible.

Functional Test - To meet the functionality objective, the unit was designed to be fully transportable, self sufficient and easily moveable. Photos (Figures 2 and 3 in this report) show that the unit is similar in size to typical hanger carts.

After demonstrating the OLCS on a portion of the oxygen lines on a C-13 aircraft, the LOX converter was charged, regulators were re-installed, and masks were connected to the regulators.

Government representatives breathed through the masks for several minutes to test the quality of the oxygen flowing through the lines that were cleaned. No noticeable odors were detected.

The JTP also requires that a test of the system functions be conducted on a B-1B mock-up system to ensure that the cleaning process has not impaired its operation. Due to several key system components not being available for the B-1B mock-up system, certain modifications had to be made to the functional test. This modification included a limited functional test on the B-1B mock-up system, but was expanded to a full range of testing on actual aircraft oxygen systems.

The complete cleaning and solvent-purging process was performed on the B-1B mock-up numerous times before the line cleaning system was used on an actual aircraft. Government personnel inspected each available system component to determine if function had been compromised in any way. No noticeable changes to component function were observed after multiple cleaning processes.

Operability Testing - Operability was based on user friendliness through the use of a touch-screen monitor. The unit has a working touch-screen monitor and can be operated by one individual rather than at team of people using solvents and rags.

LOX Compatibility (LOX Impact Test) – The Joint Test Protocol (JTP) required that the test procedure follow ASTM G86-98a *Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments*, approved September 10, 1998. A brief summary of this test procedure is available in Section 2.1 of the JTP. Initial tests showed that HFE-7100 was the top choice for Freon (CFC-113) replacement in onboard aircraft oxygen-line cleaning systems using the POCLS.

HFE-7100, a non-aqueous solvent manufactured by 3M Corporation, is non-ozone depleting, has a low global-warming potential, and is practically non-toxic. A sample of HFE-7100 was sent to an outside laboratory at White Sands Test Facility (WSTF) for LOX compatibility testing in November 1997. This test was requested before the completion of the JTP and ASTM G86-98a; therefore, the WSTF laboratory was simply instructed to perform the standard LOX compatibility tests on the sample. The test procedure used by WSTF differed from the procedure discussed in ASTM G86-98a. Reference Section 2.1.2.1 of the JTR. HFE-7100 passed these standard LOX compatibility tests, thereby allowing it to be used as a cleaning agent in the aircraft oxygen lines. The results are located in Section 4.1.1 of the JTR.

From an environmental standpoint, HFE-7100 is a very attractive replacement for CFC-113, but its effectiveness as a cleaning agent is limited. In an effort to enhance the cleaning capability of the solvent, Krytox Alcohol, a surfactant manufactured by DuPont, was added to HFE-7100. A sample of 0.10 wt.% Krytox Alcohol in HFE-7100, the maximum concentration to be considered for cleaning, was sent to WSTF for LOX compatibility testing. This solvent/surfactant solution

did not pass the necessary testing (Reference Section 4.1.1 of the JTR). The results obtained do not disqualify the use of the Krytox Alcohol/HFE-7100 mixture for onboard oxygen-line cleaning. If this mixture is to be considered for use with the OLCS, it must be proven that the surfactant can be adequately removed from the oxygen tubing before the aircraft returns to service.

Later testing has proven that a high flow velocity of neat HFE-7100 is capable of precision cleaning without the use of Krytox Alcohol. This is the preferred OLCS method because it simplifies the cleaning process since surfactant mixing and verification of removal are not required.

Materials Compatibility Test – The materials compatibility test ensures that the cleaning process will not damage any aircraft or system component. The original list of materials to be tested is given in Table 3 of the JTP. This list consists of various materials that may come into contact with the cleaning solution during the line cleaning process. Unformed material samples may not contain some of the various additives that the actual system components may possess, such as pigments, stabilizers, and plasticizers. Therefore, to ensure that the test results were indicative of actual behavior in service, actual oxygen equipment components were used for this testing.

Samples of various aircraft materials and system components were collected from Tinker AFB. The non-metallic components to be used for testing were removed as effectively as possible from their specific components. In some cases, the material could not be completely removed from their metallic housings, but enough surface was available for exposure to the cleaning solution. During a review of the materials listed in Table 3 of the JTP, no components were identified in the aircraft oxygen-plumbing system to contain Kel-F, Neoprene, Fluoro Silicone, and Vespel SP-21. Therefore, the material compatibility test was not accomplished on these materials. Multiple samples of other materials were used if considerable physical differences existed between the samples (i.e. different color, shape, surface area, etc.). Results of the material compatibility testing are found in Table 13 of the JTR.

The procedure within the JTP also required that a Gas Chromatograph (GC) be used to analyze the cleaning solution samples used to soak the tested materials. Three preliminary GC chromatograms were collected for an unused sample of the cleaning solution, a sample used for the material that lost the most weight after soaking, and a sample used for a material that lost no weight after soaking. The chromatograms are listed in Appendix C of the JTR. The resulting chromatograms were inconclusive and did not prove material compatibility; therefore, no further GC testing was done. Refer to Section 2.1.2.2 of the JTR.

#### Moisture Tests

The presence of moisture in the oxygen-distribution tubing of an aircraft presents a very serious danger. This moisture may freeze at high altitudes and cause critical valves and sensors to malfunction. Therefore, it is necessary to check the solvent drum for moisture content prior to using it for cleaning or for testing in the OLCS. If the moisture content is too high, excessive

quantities of the moisture may be left behind in the aircraft after the solvent is purged from the system.

The acceptable level of moisture in the cleaning solvent was set at 60 ppm of water. 3M Corporation, manufacturer of HFE-7100, provided moisture-test data. The test results showed that OLCS met and exceeded the specified acceptance criteria. (Results are given on page 21 of the JTP, Table 15.) HFE-7100 had moisture content of just 8 ppm and 7 ppm.

#### Non-volatile Residue Testing

The purpose of the non-volatile residue (NVR) tests was to provide a qualitative determination of how well the oxygen lines were cleaned by using a relative comparison of the NVR before and after cleaning. Refer to Section 2.3 of the JTP. Deviations from the test procedure provided in the JTP were necessary to acquire appropriate data. These modifications are discussed in Section 2.1.2.3 of the JTR. A description of the test method is outlined in Appendix D of the JTR.

The selected tests for the NVR study provided a direct method for verification of the cleanliness of the oxygen lines.

Results from the NVR tests are found in Table 14 of the JTR. Of the 14 trials conducted, nine resulted in 99% cleanliness or greater. All but one trial showed that the OLCS produced oxygen lines that were **at least** 95.28% clean. Again, most NVR trials obtained results that exceeded 99%.

#### Component/Model/System Replica Test

The purpose of this test was to verify the capability of the cleaning process on a B-1B mock-up system prior to actual platform testing. A number of test cells, as well as dead areas, were plumbed into the B-1B mock-up at various points in the system. This was to verify that each section of tubing would be exposed to an adequate solvent flow rate for proper cleaning and that all traces of solvent were removed from the system.

As stated in the previous section, the OLCS was connected to the B-1B mock-up and the complete cleaning process was performed numerous times before the OLCS was used on an actual aircraft. No solvent leaks or other irregularities were observed during the cleaning process. Adequate solvent flow was obtained at each section of tubing with no trace of solvent being observed in the dead areas after the solvent purging process was complete.

#### Dead Areas Test

This test is designed to identify redeposition areas to assure that all chemicals have been removed after cleaning is complete.

Several modifications were made to the testing procedures stated in Section A.1.7 of the JTP. These modifications are discussed in Section 2.1.2.6 of the JTR. The modified test procedures

are in Appendix G of the JTR and show that, after the halide-detector testing, dead space was removed and visually inspected. No trace of HFE-7100 was present in the dead-space volume after evacuation.

### Leak Testing

This test ensures that no significant leaks are present in the oxygen line system. Although HFE 7100 will not create electrical or mechanical problems onboard the aircraft, HFE-7100 may be discharged into the environment. There is a cost factor associated with the potential loss of HFE-7100.

The leak test procedure is listed in Section A.1.9 of the JTP. Results from the test are available in Section 4.1.9 and Appendix H of the JTR.

The leak test procedure in the JTP uses a vacuum to determine the leak rate in the aircraft tubing. This test method was used for verification, but results obtained proved to have several complications. First, if significant leaks are in fact present, contamination may be pulled from outside the aircraft tubing into the lines. Also, any soft or crimped rubber hoses or diaphragm mechanisms that may be present in flow detection devices or pressure sensors may collapse in the presence of a vacuum. This would require isolating some of the aircraft tubing from the vacuum source. Locating vacuum leaks is relatively difficult.

A method of leak testing used by Versar, Inc. included the use of a high positive pressure within the aircraft tubing. Any leaks in the system will force clean air out of the system rather than pulling contaminated air into the system. It was decided that a high-pressure test was a better representation of the actual operating conditions within the oxygen distribution system. Results from a high-pressure leak test are also provided in Section 4.1.9 of the JTR.

### Hazard Analysis

The JTP states that the hazard analysis will provide the user with acceptable operation limits in association with the Oxygen Line Cleaning Device. No specific test procedure is discussed in the JTP. Instead, the JTP says that “a test methodology developed by the NASA Johnson Space Center White Sands Test Facility and consistent with ASTM methods will be used for this analysis.” Refer to Section 2.10 of the JTP.

The focus of the hazard analysis investigation is to collect information on the components and the worst-case operating conditions. Prior to the completion of the OLCS prototype, an 85% design review was conducted, whereby representatives from both commercial and government organizations were able to observe the operation of OLCS and comment on its function. Also, careful consideration was given to any hazards or dangerous conditions that may exist while the OLCS is cleaning aircraft plumbing. The comments and suggestions made by this group were used when finalizing the safety precautions and failsafe mechanisms on the completed OLCS prototype.

The JTP also stresses the importance of considering any increased risk for fire and/or explosion when using a solvent in an oxygen rich environment. Extensive testing has proven that HFE-7100, the cleaning solvent used in the OLCS, is non-explosive in a pure oxygen environment and is unable to sustain a fire under normal operating conditions.

#### Additional Testing

The relative solvency of three different cleaning solutions was compared using various NVRs, both with and without particulate contamination (Arizona Road Dust). The three different cleaning solutions included pure HFE-7100, a 0.05 wt.% mixture of Krytox Alcohol in HFE-7100, and pure AK-225G, a reformulated version of AK-225 manufactured by Asahi Glass Co. for use by the military as an oxygen compatible solvent. These tests were performed under "no flow" conditions. This means that contaminated test surfaces were inserted into a static volume of the cleaning solution and removed after a certain amount of time. No mechanical energy was used to enhance the cleaning process.

In some cases the AK225G proved to be a much more aggressive solvent; however, in others, the HFE-7100 formulations removed somewhat more contaminant. The results of the "no flow" studies may be found in Appendix D.

A limited number of high-flow cleaning tests were also performed using the AK-225G. Various NVRs mixed with Arizona Road Dust were used as contaminants. The results from the AK-225G high-flow testing are also located in Appendix D.

#### **5.2. Data Assessment**

In addition to being an environmentally friendly technology, all collected test data shows that the use of HFE-7100 in conjunction with the OLCS provides better cleaning. It has also proved to be a more cost-effective process than the current line cleaning procedure that utilizes CFC-113.

Two of the three cleanliness verification methods required by the JTP were indirect measurement techniques. Obtaining low particles counts from the effluent solvent stream simply shows that the solvent is no longer cleaning the oxygen lines, not that the lines are cleaned effectively. The NVR testing method confirms removal by accounting for all of the NVR in the cleaning solution and the filters. Because this does not involve direct observation of the lines that were cleaned, this has proven to be a difficult task for such a large system. The third verification method, scanning electron microscopy of the test cells, was unavailable at the time of testing.

A direct method of cleanliness verification was used in all of these tests. This method involved measuring the quantity of contamination removed from the test cell compared to what was inserted into the lines that were cleaned. This data can be used to develop a process (i.e., a minimum solvent flow rate used to clean a certain size line for a minimum amount of time) that guarantees cleanliness based on prior studies of known contaminant types and quantities in aircraft tubing. However, the error associated with weighing relatively small test coupons on the available electronic scale results in imprecise values for both NVR and particulate removal.

There are a number of ways to improve the measurement of NVR and particulate quantities on the inner surfaces of the oxygen tubing. Optical probes may be used to measure the density and thickness of a specific NVR or particulate layer on the aluminum surface. Also, a larger test coupon area combined with a more accurate scale will reduce the error associated with calculating the quantity of NVR and particulate contamination remaining in the tubing test cell after the line cleaning process.

The conclusion is that it is verification that a specific process is followed that will best verify cleanliness of aircraft oxygen lines. The automated nature of the OLCS is verification that the process is followed. Particle counting and halide detection simply provide additional confidence.

## 6. Cost Assessment

### 6.1. Cost performance

This cost analysis is a high-level, preliminary, and is based on limited information. In order to fully validate this system for implementation, a more rigorous, cost saving, methodology is required such as could be provided by the JG-PP Cost Benefit Analysis approach.

**Table 2. Estimated Costs**

ESTIMATED COSTS BY CATEGORY							
Direct Process Costs				Envr. Activity Costs		Other Costs	
Start-Up		Operation & Maintenance					
Activity	\$	Activity	\$	Activity	\$	Activity	\$
Equipment purchase	200K	Labor to operate equipment	15/hr WG10	Compliance audits	N/A	Overhead assoc. with process	Incl O&M
Equipment design	75K	Labor to manage haz. waste	-0-	Document maintenance	N/A	Productivity/Cycle time	2-8 Hr Size AC
Site preparation	-0-	Utilities (Electricity_	\$1/hr	Envr. Mgmt. plan development & maintenance	N/A	Worker injury claims & health costs	-0-
Installation & Construct Labor	200K	Mgmt/Treatment of by-products	N/A	Reporting requirements	N/A		
Life of equipment (Estimated)	10 Yrs	Haz. waste disposal fees	\$50/yr	Test/analyze waste streams	N/A		
Training of operators (1 Month)	12.5K	Consumables & supplies	10K/year	Medical exams (incl. loss of productive labor)	-0-	No Hazardous Waste Involved. Solid Waste Only	
		Equipment maintenance	10K/Year	Waste transportation (on and off-site)	Incl. In O& M.		
		Labor Management Solid Waste	\$50/Year	OSHA/EHS training	N/A		

### 6.2. Cost Comparisons to Conventional and Other Technologies

Conventional costs associated with cleaning a contaminated B-1B are estimated to be \$1M in labor and 15 plus gallons of CFC-113. The estimated cost to clean the same aircraft with the OLCS is less than \$2,500. These costs are based on a requirement to clean an entire

contaminated system. There are no other existing technologies to compare to this technology. Current cleaning methods employ only a manual method of cleaning. This manual method entails disassembly of the aircraft plumbing system, individually cleaning the system components with a CFC-113 rinse, and reassembly of the aircraft plumbing system. It is very doubtful that all oxygen lines can be accessed for removal by this cleaning process. There are no consistently applied cleaning or verification processes with this out-dated manual method.

## **7. Regulatory Issues**

### **7.1. Approach to Regulatory and End-User Acceptance**

Due to the nature of the chemical choices, regulatory issues have been negated. There is no volumetric waste generated. Waste disposal consists of filter socks and residual sludge from chemical distillation process. These filter socks contain no hazardous material; therefore, they can be disposed of in a landfill. Residual sludge may contain certain oils removed from the aircraft oxygen lines; however, the amount will be minimal and can be disposed of along with other industrial waste.

## **8. Stakeholder/End-User Issues**

The contaminants and particulates within aircraft oxygen systems can pose significant hazards to both aerospace vehicles and personnel. Hydrocarbon contaminates and particulates impinging on surfaces from gas streams of pure or highly concentrated oxygen can be sources of ignition and have been identified as a possible source of fires on military vehicles. Such particulates also pose a significant health threat to personnel, as emphasized in EPA revised guidelines for particulate matter.

One primary concern expressed by the three aircraft stakeholders is that there is no current requirement that a full-system cleaning be performed on military aircraft. Until now, oxygen lines could not be cleaned without disassembly of the entire aircraft-oxygen system. Cleaning aircraft-oxygen lines with this new technology represents a new methodology in oxygen-line maintenance.

Establishing and implementing a requirement rests with the individual program offices.

Another concern expressed by stakeholders was the size of the prototype cart. Prior methods of oxygen-line cleaning did not require any use of support equipment, only solvent and rags. The prototype cart is a 12' X 7' trailer similar to the size of many pieces of support equipment currently used on aircraft flight lines; therefore, the cart should fit in any existing hangar. The cart prototype is sized to accommodate large aircraft, and systems and can be adapted for smaller aircraft and similar systems.

## **9. Technology Implementation**

### **9.1. DoD Need**

Various requirements exist in the Air Force needs database (which is currently protected from public access) from which this project was initiated. The needs are categorized by weapons system and vary in applications. Most weapons systems address a need for replacement of CFC-113 in cleaning applications. This project targets the ODC as well as the method of cleaning. The need for a replacement chemical for CFC-113 is a DoD-wide problem with this project targeting an accepted and utilized process. There are many potential opportunities for technology transfer throughout the DoD.

### **9.2. Transition**

Transition of this plan can take two paths: continued transition to other military aircraft or transition into the civilian industry.

Developing a standard requirement for the cleaning process is the next step in transitioning this technology. This effort will be directed to HQ AFMC/EN engineering division. Demonstrations at various locations will be required to validate the OLCS on each type of weapons system; therefore, additional funding will be needed. To implement the OLCS, program offices will have to develop technical-order procedures for each weapons system. These efforts are currently being addressed by personnel at Tinker AFB, OK, via memorandums to HQ AFMC.

The opportunity exists for this technology to transfer to all aircraft OEMs if requirements are established by the Air Force.

Transitioning this technology to the civilian industry will require partnering. A partnership is being investigated with BOC Gases in Dayton, Ohio. Versar Inc. is addressing this. The gas industry installs and certifies medical oxygen systems in dental offices and medical facilities. Their certification process is similar to standard aircraft-oxygen-line maintenance requiring a hot-nitrogen purge and certification by a Food and Drug Administration authority (within the company).

## **10. Lessons Learned**

It is important to document and share lessons learned to help prevent planning errors and to help future efforts. The following are lessons learned.

- Due to unexpected developments, the program became more extensive than originally anticipated.

- Initial concepts will change with the course of development and may require modifications to the project. This was done to replicate the true need of the motivating problem and accomplish the intended goal in a timely manner.
- Unanticipated personnel changes have a drastic effect on any program over the course of a four-year project. This has happened on the government and contractor side of the project, and experience has shown that this is an area that should be budgeted for.
- The ESTCP office was exceptionally responsive to the developmental arena and fully understanding of programmatic changes. Inform them as early as possible of any anticipated programmatic or budgetary changes.
- Technical specifications described in equipment catalogs were misleading. Much of the equipment ordered to construct the prototype did not perform to the specifications listed in the parts catalogs. Also, the delivery of components was not always as specified by the vendor. At certain times, a delay in shipment lasted two to six months, causing project delays.
- Ensure funding is requested for implementation as well as development. Implementation is a difficult and time-consuming process that can take longer than originally anticipated.

## **11. References**

*Demonstration Test Plan*, the Versar Test Plan and Procedures are attached to the JTP as Appendix A.

*Final Joint Test Protocol (JTP)*, J-99-CL-015-P1, *for Validation of Alternatives to Ozone-Depleting Chemicals Used in Oxygen-Line Cleaning*, National Defense Center for Environmental Excellence (NDCEE) for the Engineering and Technical Services for Joint Group on Pollution Prevention (JG-PP), July 24, 2001.

*Environmental Cost Analysis Methodology (ECAM) Handbook*, National Defense Center for Environmental Excellence for the Environmental Security Technology Certification Program, November 1997.

*Joint Test Report (JTP)*, J-99-CL-015-R1, *for Validation of Alternatives to Ozone-Depleting Chemicals Used in Oxygen-Line Cleaning*, Concurrent Technologies Corporation for Engineering and Technical Services for Joint Group on Pollution Prevention (JG-PP) Projects, September 4, 2002.

**Appendix A**  
**Joint Test Report**

**Engineering and Technical Services  
for Joint Group on Pollution  
Prevention (JG-PP) Projects**

**Joint Test Report  
J-99-CL-015-R1**

**for Validation of  
Alternatives to Ozone Depleting Chemicals Used in  
Oxygen Line Cleaning**

**September 4, 2002**

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Task Order Number: 5TS5701D056  
Contract Number: GS-23F-0061L  
Data Item Number: A016-09

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## PREFACE

This report was prepared by Concurrent Technologies Corporation (*CTC*) through the General Services Administration (GSA) under Contract Number GS-23F-0061L. This report was prepared on behalf of, and under guidance provided by, the Joint Group on Pollution Prevention (JG-PP) Working Group. The structure, format, and depth of technical content of the report were determined by the JG-PP Working Group, government contractors and other government technical representatives in response to the specific needs of this project.

We wish to thank the participants involved in the creation of this document for their invaluable contributions; Tinker Air Force Base (AFB), Robins AFB, the Oklahoma Air National Guard (ANG), Tulsa ANG Base, and the B-1, B-2, F-15, and F-16 aircraft programs.

This Joint Test Report (JTR) documents the results of testing performed in accordance with the *Joint Test Protocol (J-99-CL-015-P1) for Validation of Alternatives to Ozone Depleting Chemicals Used in Oxygen Line Cleaning*, dated July 24, 2001. This JTR will be made available as a reference for future pollution prevention endeavors by other U.S. Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and industry organizations to minimize duplication of effort.

## EXECUTIVE SUMMARY

The Joint Logistics Commanders (JLC) and Headquarters National Aeronautics and Space Administration (NASA) co-chartered the Joint Group on Pollution Prevention (JG-PP) to coordinate joint service/agency activities affecting pollution prevention issues identified during system and component acquisition and sustainment processes. The primary objectives of the JG-PP are to:

- Reduce or eliminate the use of hazardous materials (HazMats) or hazardous processes at manufacturing, remanufacturing, and sustainment locations
- Avoid duplication of effort in actions required to reduce or eliminate HazMats through joint service cooperation and technology sharing.

For each project, a Joint Test Protocol (JTP) is written containing the critical requirements and tests necessary to qualify potential alternatives to selected target HazMats and processes for a particular application. The required tests for this project are documented in *Joint Test Protocol (J-99-CL-015-P1) for Validation of Alternatives to Ozone Depleting Chemicals Used in Oxygen Line Cleaning*, dated July 24, 2001, hereafter referred to as JTP.

Typically, during each project, the participating technical representatives select candidate alternatives that will be tested in accordance with the JTP, and a Potential Alternatives Report (PAR) evaluating these alternatives is written. For this project, a PAR was not conducted. Chlorofluorocarbons (specifically CFC-113) and hydrochlorofluorocarbons (specifically HCFC-141b) were identified as the target HazMats to be eliminated or reduced for the “Validation of Alternatives to Ozone Depleting Chemicals Used in Oxygen Line Cleaning” project; the identified process was equipment cleaning. The identified application is oxygen line cleaning of aerospace vehicles, surface ships, and submarines. The substrates may be aluminum, stainless steel, or copper. Two alternative technologies were chosen for this project: an alternative zero ozone depleting cleaning solvent and an aqueous cleaning system.

Two methods of cleaning were tested for qualification: onboard aerospace vehicle cleaning (i.e., cleaning in place) and off-aircraft cleaning. The alternative cleaning solvent tested onboard used equipment provided by Versar and the solvent tested off-aircraft used equipment provided by Northrop Grumman. In addition, an aqueous cleaner was tested using an off-aircraft cleaning system called the Navy Oxygen Cleaning System (NOCS).

Once project participants define the tests to be performed and the alternatives to be tested, testing is executed. This Joint Test Report (JTR) documents the results of the testing, describes any test modifications made during the execution of testing, and identifies technically acceptable alternatives to the baseline process. Technical stakeholders were advised of all test procedure modifications documented in this JTR. There was no test conducted per the JTP requirements that failed to meet the acceptance criteria set in the JTP. This report summarizes the testing conducted and the results.

The information contained in this report is presented to enable potential users of these systems/solvents to decide if they are feasible for their application. These systems/solvents can potentially be utilized to clean almost any type line (hydraulic, fuel, coolant, environmental, etc.) on several different applications, such as tanks, machinery, and hospital oxygen lines.

Additional engineering and testing would be required to adapt this technology to a specific application, but the transition should not pose any problems. The onboard aerospace vehicle and off-aircraft cleaning technology is available to both military and commercial customers.

## 1.0 INTRODUCTION

The Joint Logistics Commanders (JLC) and Headquarters National Aeronautics and Space Administration (NASA) co-chartered the Joint Group on Pollution Prevention (JG-PP) to coordinate joint service/agency activities affecting pollution prevention issues identified during system and component acquisition and sustainment processes. The primary objectives of the JG-PP are to:

- Reduce or eliminate the use of hazardous materials (HazMats) or hazardous processes at manufacturing, remanufacturing, and sustainment locations
- Avoid duplication of effort in actions required to reduce or eliminate HazMats through joint service cooperation and technology sharing.

JG-PP projects typically involve at least one original equipment manufacturer (OEM), producing multiple systems for more than one of the Department of Defense (DoD) Services or NASA, as well as at least one facility, such as a DoD depot, maintaining one or more of the systems. JG-PP technical representatives for each project begin by selecting at least one target HazMat for reduction or elimination. This target HazMat is a material used in production or sustainment processes that is known to create environmental and/or worker health concerns. Project participants then identify alternative technologies or materials for evaluation.

For each project, a Joint Test Protocol (JTP) that contains the critical requirements and tests necessary to qualify potential alternatives to selected target HazMats and processes for a particular application. The required tests for this project are documented in *Joint Test Protocol (J-99-CL-015-P1) for Validation of Alternatives to Ozone Depleting Chemicals Used in Oxygen Line Cleaning*, dated July 24, 2001, hereafter referred to as JTP. The tests are summarized in Section 2 of this document.

During each project, the participating technical representatives select candidate alternatives that will be tested in accordance with the JTP. The alternative selection process for this project was completed by the stakeholders; therefore, a Potential Alternatives Report (PAR) was not conducted. The alternatives are listed in Section 3.

After project participants define the tests to be performed and the alternatives to be tested, testing is executed. This Joint Test Report (JTR) documents the results of the testing, describes any test modifications made during the execution of testing and identifies technically acceptable alternatives to the baseline process. Test procedure modifications documented in this JTR have been agreed upon by the project technical stakeholders.

Chlorofluorocarbons (specifically CFC-113) and hydrochlorofluorocarbons (specifically HCFC-141b) were identified as the target HazMats to be eliminated or reduced for the “Non-Ozone Depleting Chemicals Used in Oxygen Line Cleaning” project. The identified process was equipment cleaning. The identified application is oxygen line cleaning of aerospace vehicles, surface ships, and submarines. The substrates may be aluminum, stainless steel, or copper. Table 1 summarizes the target HazMat, process and

material, application, current specifications, affected programs, and candidate parts/substrates.

**Table 1. Oxygen Line Cleaning System Target HazMat Summary**

<b>Target HazMat</b>	<b>Current Process</b>	<b>Applications</b>	<b>Current Specifications</b>	<b>Affected Programs</b>	<b>Candidate Parts/ Substrates</b>
Ozone depleting chemicals (CFC-113, HCFC-141b)	Flushing CFC-113 or HCFC-141b through contaminated oxygen lines, and released directly to atmosphere	Aerospace vehicles  Navy: Removed oxygen lines only (JTP Sec. 3)	MIL-STD-1330D MIL-STD-1359 SAE ARP-1176 A-A-50427  Individual vehicle Technical Orders	<u>Air Force:</u> B-1, B-2, F-15, F-16 <u>Navy:</u> eventually all platforms <u>NASA:</u> Orbiter	Aluminum, stainless steel, copper

## 2.0 Testing Requirements and JTP Deviations

### 2.1 Oxygen Line Cleaning Onboard Aerospace Vehicles

#### 2.1.1 Testing Requirements

A joint group led by JG-PP, and consisting of technical representatives from Oklahoma City Air Logistics Center (OC-ALC), NASA, Naval Air Systems Command (NAVAIR), Northrop Grumman, B-1, B-2, F-15, and F-16 weapon system personnel, identified engineering performance criteria for oxygen line cleaning onboard aerospace vehicles (i.e., cleaning in place). This group reached consensus on the test conditions and acceptance criteria to qualify alternatives against these critical technical and performance requirements. These tests were identified for a number of application categories. Failure in any test does not necessarily disqualify a candidate alternative for use in all possible applications. The selection criteria may not be useful for all applications in all instances.

Table 2 lists all engineering and test requirements identified by the JG-PP participants for validating alternatives to CFC-113 and HCFC-141b used in onboard oxygen line cleaning. All affected programs require these common tests.

Tests were conducted in a manner that eliminated duplication and maximized use of each test specimen. For example, where possible, more than one test was performed on each specimen. The amount and type of tests that were run on any one specimen were determined by the destructiveness of the test.

**Table 2. Common Engineering and Test Requirements for Oxygen Line Cleaning Onboard Aerospace Vehicles**

Test	Test Platform	JTP Section	Acceptance Criteria	References
LOX Impact	Laboratory <sup>1</sup>	2.1	Zero reactions for 20 successive impacts at 98 J (72 ft-lb <sub>f</sub> )	ASTM G86
Materials Compatibility	Laboratory <sup>1</sup>	2.2	No visible or permanent evidence of substrate deterioration	ASTM G127 Versar Test Plan
Nonvolatile Residue (NVR)	B1-B Mock-up & Actual <sup>2,3</sup>	2.3	To be defined by each platform, but generally <u>Level A:</u> NVR ≤ 1 mg/sq. ft. <u>Level B:</u> NVR ≤ 2 mg/sq. ft. <u>Level C:</u> NVR ≤ 3 mg/sq. ft. <u>Orbiter:</u> NVR ≤ 0.3 mg/sq. ft. <u>Baseline</u> (before soiling): NVR ≤ 0.3 mg/sq. ft.	ASTM F331 SAE ARP1176
Moisture	Laboratory <sup>1</sup>	2.4	Less than 60 ppm water by weight	ASTM D5530
Cleanliness Verification	B1-B Mock-up & Actual <sup>2,3</sup>	2.5	Particle count in low-pressure systems (except Orbiter LOX): ≤ 300 Particle count in Orbiter (LOX): ≤ 50 Particle count in high-pressure systems ≤ 200 for all platforms Baseline particle count ≤ 25	ASTM G93 ASTM F312 SAE ARP1176 Versar Test Plan

**Table 2. Common Engineering and Test Requirements for  
Oxygen Line Cleaning Onboard Aerospace Vehicles (Continued)**

Test	Test Platform	JTP Section	Acceptance Criteria	References
Functional Test	Actual <sup>3</sup>	2.6	Oxygen line system function and operation has not been impaired by the cleaning process. Acceptable oxygen will have no odor and no constituents, per the Test Methodology	Aircraft T.O. MIL-PRF-27210G
Component/ Model/System Replica Test	B1-B Mock- up <sup>2</sup>	2.7	Cleanliness verification per JTP Sec. 2.5 B-1B mock-up oxygen line system function and operation has not been impaired by the cleaning process	Versar Test Plan
Dead Areas	B1-B Mock- up <sup>2</sup>	2.8	No significant difference in NVR Cleaner concentration in air purge stream is continuously below 600 ppm	ASTM G88
Leak Testing	B1-B Mock-up & Actual <sup>2, 3</sup>	2.9	TBD - Determined from system volume a function of the type of aerospace vehicle	Versar Test Plan
Hazard Analysis	Laboratory <sup>1</sup>	2.10	To be determined by the user, data report only	NASA TM-104823

1. "Laboratory" means that the testing will be performed in a laboratory environment prior to testing the portable OLCS.
2. "B1-B Mock-up" means testing will be performed on the B1-B oxygen system mock-up.
3. "Actual" means verified and validated by actual aircraft.

The substrate type to be used for construction of the test cells is aluminum alloy 2024-T3. The specimens are cut-away parts of the actual oxygen line.

Table 3 lists the substrate types that are used for materials compatibility testing. All of these substrates are required by the Air Force, NASA, and Navy.

**Table 3. Test Specimen Codes and Substrate Descriptions for Compatibility Testing**

Test Specimen Code	Substrate Description
SR	Silicone rubber
KEL	Kel-F. (DuPont Product)
NP	Neoprene
FS	Fluoro Silicone
VES	Vespel SP-21
NYL	Nylon
TEF	Teflon
PS	Polysulfone
CYC	CycloLak (DuPont Product)
SIL	Silicone
NR	Nitril Rubber
PC	Polycarbonate

**Table 3. Test Specimen Codes and Substrate Descriptions for Compatibility Testing  
(Continued)**

<b>Test Specimen Code</b>	<b>Substrate Description</b>
PVC	Polyvinyl chloride
VIT	Viton (Fluoro Elastomer)
EWI	Electrical wiring insulation, Cannon Plugs
CPP	Cockpit plastic panels

Table 4 lists the soils with which the oxygen lines will be contaminated before cleaning.

**Table 4. Test Contaminants to be used for Oxygen Line Cleaning Onboard  
Aerospace Vehicles**

<b>Name</b>	<b>Description</b>	<b>Organization Requiring Contaminant</b>
WD-40	Multi-purpose lubricating oil	NAVAIR Northrop Grumman
MIL-PRF-7808	Ester based turbine oil	NAVAIR (TBD) Northrop Grumman
MIL-H-5606	Mineral oil hydraulic fluid	NAVAIR (TBD) Northrop Grumman
MIL-PRF-27617	Fluorinated grease (Krytox 240AC used for test)	NAVAIR Northrop Grumman
MIL-C-47220	Coolanol, silicate-ester based coolant	Air Force
MIL-PRF-87252	Polyalphaolefin (PAO), coolant	Air Force
MS-139	Coolant	Northrop Grumman
Amberlube EC-98	Tube bending oil	Northrop Grumman, Air Force
Arizona Road Dust (ARD): 68% SiO <sub>2</sub> , 16% AlO <sub>2</sub> , 5% FeO <sub>2</sub> , 4.5% NaO <sub>2</sub> , 3% CaO <sub>2</sub> , 3.5% organics	Particulate	Air Force
Zeolite and binder (Type 13X)	Particulate	Air Force
Zeolite and binder (Type 5A)	Particulate	NAVAIR
MIL-PRF-83282C	Synthetic hydraulic fluid	Air Force, NASA, NAVAIR
HFE-7100 <sup>a</sup>	Solvent	Air Force
Acetone	Solvent	Air Force
Water <sup>a</sup>	Solvent	Air Force
	Silicon grease	Air Force
MIL SPEC Detergent	Aqueous detergent residue	Air Force
	Hydrocarbon grease	Air Force

<sup>a</sup> These are not contaminants themselves, but rather carriers for the cleaning solvent. It is necessary to make sure all traces of these materials are removed from the oxygen lines.

## **2.1.2 Test Modifications**

When this program was chosen to become a joint program requiring a JTP, test parameters and procedures were specified to meet all requirements of the various organizations. These tests were derived from engineering, performance, and operational impact requirements defined by a consensus of government and industry participants. These testing requirements are identified in the JTP. In executing some of the tests, deviations from the described procedure became necessary to accomplish the intended goal. These deviations were agreed upon with the stakeholders and are described in detail in Section 2.1.2.1 through Section 2.1.2.6 below. Each of these sections include a representative description of the original JTP test; a description of the test modification; and the rationale for deviating from the original test procedure. For reference purposes, each test is identified by its corresponding JTP section number.

### **2.1.2.1 LOX Impact Neat Chemical Test – JTP Section 2.1**

#### **Original Test Procedure**

The original JTP procedure instructed that ASTM G86-98a (*Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments*, approved September 10, 1998) be used for the ambient and pressurized liquid oxygen (LOX) impact tests.

#### **Test Procedure Modifications**

Due to the nonavailability of ASTM G86-98a at the time of testing, LOX compatibility tests were performed by White Sands Test Facility (WSTF) using two different test methods. NASA Handbook 8060.1C Test 13A was used for the ambient pressure test and ASTM G72 (*Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment*) was used for the high pressure test.

Going beyond the scope of the JTP, a LOX impact test was conducted on a mixture of 0.10 wt.% Krytox Alcohol (surfactant) in HFE-7100.

#### **Rationale**

The original test method requires LOX impact tests on the solvent at both ambient and high pressure using ASTM G86-98a. The rationale for using these alternate tests was that they were accepted as standard tests for LOX compatibility testing at ambient and high pressure at the time of testing. These alternate standards accomplish the intent of the original LOX impact tests and are acceptable by today's standards.

LOX impact testing on the surfactant/solvent mixture was completed to determine acceptance when surfactants are used to improve the cleaning ability of solvents.

### 2.1.2.2 Material Compatibility – JTP Section 2.2

#### Original Test Procedure

The original JTP procedure instructed the user to expose the materials listed in Table 3 to the test solvent/surfactant mixture. In addition to using the accepted industry standard ASTM G127 (*Standard Guide for the Selection of Cleaning Agents for Oxygen Systems*, approved June 15, 1995), this test also specifies the use of a gas chromatograph (GC) for solvent identification.

#### Test Procedure Modification

The materials chosen in Table 3 of the JTP were identified as potentially being part of the oxygen equipment components that might come into contact with the solvent during cleaning. During a review of manufacturers' data and obtainment of equipment for testing, no components were identified in the aircraft oxygen plumbing system that contains Kel-F, Neoprene, Fluoro Silicone, and Vespel SP-21.

GC testing was not conducted as extensively as stated in the JTP; it was only conducted on a limited basis.

#### Rationale

Unformed material samples, which are raw materials that have not been subjected to component processing, may not contain some of the various additives that the actual system components may possess, such as pigments, stabilizers, and plasticizers. Therefore, to ensure that the test results were indicative of actual behavior in service, actual oxygen equipment components were used for this testing. This method ensures that the results obtained are consistent with actual component behavior during service. If equipment is later identified that contains any of the materials that were not tested, then specific material compatibility testing can be accomplished at that time.

The GC testing was performed on a small number of samples to determine validity of this test method. The resulting chromatograms were inconclusive and did not prove material compatibility for oxygen line cleaning.

### 2.1.2.3 Nonvolatile Residue Test – JTP Section 2.3

#### Original Test Procedure

This test determines the amount of nonvolatile residue (NVR) remaining after cleaning. The JTP specifies that testing be completed per ASTM F331 [*Standard Test Method for Nonvolatile Residue of Solvent Extract from Aerospace Components (Using Flash Evaporator)*, approved October 10, 1998]. The procedure is a bench-scale test used for testing oxygen equipment cleanliness.

## **Test Procedure Modification**

Modifications were made to this test to provide a qualitative determination of how well the oxygen lines were cleaned by using a relative comparison of the NVR before and after cleaning. This deviation included devising a new test procedure to accomplish the NVR test. A description of this test method is outlined in Appendix D. Versar tested only seven of the contaminants listed in Table 4 of the JTP as these are the only ones considered to be nonvolatiles.

## **Rationale**

The rationale for devising a new test procedure was to provide the appropriate data necessary to achieve the intended goal of the JTP. This goal is to provide a qualitative determination of how well the OLCS removed various nonvolatile contaminants from the inner surfaces of aircraft tubing. The developed test cell method of direct contaminant measurement using cells in full scale aircraft plumbing mock-ups is used to establish optimum processes for a given aircraft type. An optimum process is one that takes into account the oxygen pressure and oxygen flow rates that the contaminant is exposed to in service. In addition, the sensitivity of components such as regulators and valves in the oxygen system are considered. Results obtained from the verification process cannot be directly compared to those of a more conventional process. The process and philosophy of complete system cleaning must be considered independently. It is not an alternative to the conventional cleaning process, but a compliment to the process in the appropriate given situation.

The original test procedure was designed from a bench-scale test. Due to the design characteristics and the size of the OLCS, there is no practical way to capture the effluent solvent for NVR analysis. The minimum quantity of solvent needed to circulate through the system for a single test was approximately 20 liters. The time required to evaporate the solvent from the accumulated NVR would take many hours for each test. The potential error associated with trying to measure such small quantities of NVR in large filter elements and from large quantities of fluid makes the JTP procedure ineffective. However, the modified procedure does accomplish the intended goal of providing a qualitative determination of how well the oxygen lines were cleaned.

### **2.1.2.4 Cleanliness Verification Test – JTP Section 2.5**

#### **Original Test Procedure**

The original test procedure states that this test determines the cleanliness level of a test article by determining particle counts, NVR, and surface particulate verification by using a scanning electron microscope (SEM).

## **Test Procedure Modification**

Certain modifications had to be made to this test because a SEM was not used. The cleanliness of the test coupons were visually verified using digital photos before contamination, after contamination, and after cleaning.

The particle count testing of the effluent stream was another modification that had to be made to the cleanliness verification test. Versar used a method they considered more direct to verify cleanliness of the lines, rather than the original technique that was an indirect verification method.

## **Rationale**

Availability of a SEM is anticipated at a later date and verification of the test coupons could be achieved at that time.

The rationale in using the alternate method of cleanliness verification is that Versar considered a particle count of the effluent stream as ineffective in determining the cleanliness of the test cell. While the particle count data is directly measurable with the particle counter in the OLCS, laboratory test have proven that it is ineffective in determining the cleanliness of the test cell. Therefore, cleanliness verification was achieved by using the same methodology as the NVR test. The required cleaning procedure (wash cycle time, rinse cycle time, solvent flow velocity) was based on prior bench-scale laboratory cleanliness testing. Since flow rates and times to accomplish adequate cleaning will vary depending upon anticipated contaminant, line size, length, complexity, and the level of cleaning required for specific aircraft, additional tests were performed using increased flow rates and times.

### **2.1.2.5 Functional Test – JTP Section 2.6**

## **Original Test Procedure**

The original test procedure states that a functional test be conducted on the B-1B mock-up system after being cleaned with the prototype OLCS. Acceptable oxygen will have no odor and no constituents greater than the levels stated in Table I of MIL-PRF-27210G.

## **Test Procedure Modification**

Due to several key system components not being available for the B-1 mock-up system, certain modifications had to be made to the functional test. This modification included a limited functional test on the B-1 mock-up system, but was expanded to a full range of testing on actual aircraft oxygen systems

Another modification to the functional test was the verification of solvent removal by an oxygen purity test. This test was accomplished using an onboard halide detector in conjunction with a dry air purge.

## **Rationale**

The intent of the functional test was accomplished in that the OLCS process was demonstrated on a B-1 mock-up as well as actual aircraft with no system degradation or malfunctions being observed. These aircrafts include the B-1B, F-15, F-16, and C-130. All components on the aircrafts performed properly after completion of the oxygen line cleaning process, as well as no odor being detected.

After demonstrating the OLCS on a portion of the oxygen lines on a C-130 aircraft, the LOX converter was charged, regulators were re-installed, and masks were connected to the regulators to test the quality of the oxygen flowing through the lines that were cleaned. No problems were indicated.

The oxygen purity test ensures that no significant quantities of the constituents listed in Table I of MIL-PRF-27210G are present in the aircraft tubing. Of the constituents listed, only a halogenated compound (HFE-7100) is introduced into the aircraft during cleaning. Upon completion of the wash and rinse cycle, the OLCS process utilizes a vacuum to remove the solvent from the aircraft. Any residual solvent is purged using a dry air stream and can be measured down to parts per million (ppm) concentrations using a halide detector.

#### **2.1.2.6 Dead Area – JTP Section 2.8**

##### **Original Test Procedure**

The original test procedure is designed to identify redeposition areas to assure that all chemicals have been removed after cleaning is complete. This is performed by using four different and distinct tests with the first one specifically following the ASTM G88 (*Standard Guide for Designing Systems for Oxygen Service*, approved June 29, 1990) and the following three using the test cells in various dead areas.

##### **Test Procedure Modification**

There were several modifications made to the dead area test procedure; the JTP requests that the first test specifically follow the ASTM G88. This ASTM does not provide any specific test method; therefore, there was no test to be performed. The ASTM G88 is simply a design guide for oxygen service equipment used in oxygen-enriched environments. Since the OLCS does not utilize enriched oxygen in any way, the use of this design guide was not necessary.

Dead Area Test #1 and #2 in the JTP are designed to measure the redeposition and removal of surfactant in dead areas of the aircraft tubing. Since no surfactant was used for the cleaning process, these tests were not necessary.

## 2.2 Off-Aircraft Oxygen Line Cleaning

### 2.2.1 Testing Requirements

Engineering performance for off-aircraft oxygen line cleaning (i.e., cleaning contaminated oxygen lines removed from the aircraft) was identified by a joint group led by JG-PP and consisting of technical representatives from NAVAIR, OC-ALC, NASA, B-1, B-2, and Northrop/Grumman. This group then reached consensus on tests with procedures, methodologies and acceptance criteria to qualify alternatives against these critical technical and performance requirements.

Table 5 and Table 6 list all engineering and test requirements identified by the JG-PP participants for validating alternatives to CFC-113 and HCFC-141b used for off-aircraft oxygen line cleaning. Table 5 lists the common tests, which are required by all affected programs. Table 6 lists the extended tests, which are required by at least one of the programs, but not all. This listing includes acceptance criteria and the references, if any, used for developing the tests.

**Table 5. Common Engineering and Test Requirements  
for Off-Aircraft Oxygen Line Cleaning**

Test	JTP Section	Acceptance Criteria	References
Nonvolatile Residue (NVR)	3.1	Navy (Navy Oxygen Cleaner [NOC] process): 5 ppm by wt. <sup>a</sup> maximum NVR above baseline in final NOC cleaner Air Force/B-1 & NASA: 9.3 ppm by wt. maximum NVR above baseline in final NOC cleaner Northrop/Grumman: See T.O. 15-X-1-1	MIL-STD-1330D Appendix B (Navy NOC process) ASTM G121

<sup>a</sup> Caution when converting volume to area. { 1liter = .035 ft<sup>3</sup> } X<sup>3</sup>= 3(X)<sup>2</sup>

Per MIL-STD-1330D: 1Liter volume tested (Mil Std 1330D Appendix B) = (.035) ft<sup>3</sup>= 3 (.035) ft<sup>2</sup> = .105 ft<sup>2</sup> OR  
1mg NVR allowed (i.e 5ppm<sub>max</sub> equivalent to 1 mg<sub>max</sub>) per .105 ft<sup>2</sup> = 9.5 mg/ft<sup>2</sup> equivalent to 5ppm<sub>by wt</sub>

**Table 6. Extended Engineering and Test Requirements  
for Off-Aircraft Oxygen Line Cleaning**

Test	JTP Section	Acceptance Criteria	References	Programs Requiring Test
Soil Removal	3.2	See T.O. 15-X-1-1	ASTM G121 ASTM G122	Northrop/Grumman/B-2
Particle Count (PC)	3.3	Level 50, as follows (particle count per liter) < 10 um - unlimited 15-25 um - 17 25-50 um - 8 > 50 um - 0	MIL-STD-1246C Sec. 5.1.2.3 Table III Gases ASTM F-312 or ASTM F-328 & F-649 NASA JPG 5322.1 Rev D Level 50	NAVAIR NASA
Water Content	3.4	7 ppm maximum water in N <sub>2</sub> purge	MIL-PRF-27210G CGA G-4.3	NAVAIR

Tests identified in Tables 5 and 6 are further defined below to include test description, rationale, and methodology. Also included, as needed, are any major or unique equipment, and data reporting and analysis procedures. Test methodology includes the definition of test parameters, test specimens, number of trials per specimen, any experimental control specimens required, and acceptance (pass/fail) criteria.

Table 7 is a listing of substrate types that are candidates for testing.

**Table 7. Test Specimen Codes and Substrate Descriptions  
for Off-Aircraft Oxygen Line Cleaning**

Test Specimen Code	Substrate Description	Organization Requiring Contaminant
AL1	Aluminum 6051 T6	NAVAIR
AL2	Aluminum 2024	Air Force/B-1
AL3	Aluminum 5051	Northrop/Grumman/B-2
CU1	Pure copper	NAVAIR
SS1	Stainless steel 304	NAVAIR

Table 8 lists the materials to be used in the testing to contaminate the oxygen lines before cleaning.

**Table 8. Test Contaminants to be Used for Off-Aircraft Oxygen Line Cleaning Testing**

Name	Description	Organization Requiring Contaminant
WD-40	Lubricant	NAVAIR, Northrop/Grumman/B-2
Krytox 240 AB Fluorinated Grease	Lubricant	NAVAIR
Oakite Drawsyn	Tube bending fluid	NAVAIR
Hydraulic Fluid 83282C	Hydraulic fluid	NAVAIR
MIL-PRF-7808	Oil	Northrop/Grumman/B-2
MIL-H-5606	Hydraulic fluid	Northrop/Grumman/B-2
MS-139	Coolant	Northrop/Grumman/B-2
Amberlube EC-98	Tube bending lubricant	Northrop/Grumman/B-2
Braycote 660	Fluorinated grease	Northrop/Grumman/B-2
MIL-PRF-27617	Hydrocarbon grease	Northrop/Grumman/B-2

The above soils will be applied to the test parts per ASTM G121-98 (*Standard Practice for Preparation of Contaminated Test Coupons for the Evaluation of Cleaning Agents*, approved September 10, 1998).

Table 9 shows the sizes of the oxygen lines to be tested and the quantity of contaminants to be applied. These line sizes are based on Navy (only) requirements that lines not exceed six feet in length and one inch in diameter. The Navy is restricted by the size of the tanks currently used by their fleet for component cleaning (capacity is 1.9 gallons).

**Table 9. Line Sizes and Soil Loadings to be Used for Off-Aircraft Oxygen Line Cleaning Testing**

Line Size (feet)	Soil Loading	Line Outer Diameter (inches)
2	Liquid contaminants: 3 cc Grease: 3 g	≤ 1
4	Liquid contaminants: 6 cc Grease: 6 g	≤ 1
6	Liquid contaminants: 9 cc Grease: 9 g	≤ 1

### 2.2.2 Test Modifications

As stated in Section 2.1.2, when this program was chosen to become a joint program requiring a JTP, test parameters and procedures were specified. As the development effort proceeded not all the participants submitted expected test data. The following are

explanations of each test requirement and whether the tests were conducted as specified by the JTP.

#### **2.2.2.1 Nonvolatile Residue**

The JTP stated that this test applied to both the NOC and Northrop Grumman systems. However, test data was only received from NAVAIR for the NOC System.

#### **2.2.2.2 Soil Removal**

Northrop Grumman submitted samples contaminated with Arizona Road Dust (ARD) with either distilled water or Krytox grease. The JTP lists seven contaminants for this test, none of which were tested.

#### **2.2.2.3 Water Content**

No water content testing was conducted.

### 3.0 ALTERNATIVES TESTED

Two alternative technologies were chosen for this project - an alternative zero ozone depleting cleaning solvent and an aqueous cleaning system. Two methods of cleaning were tested for qualification - onboard aerospace vehicle cleaning (i.e., cleaning in place) and off-aircraft cleaning.

The alternative cleaning solvent tested onboard utilized equipment provided by Versar and off-aircraft utilized equipment provided by Northrop Grumman. In addition, an aqueous cleaner was tested using an off-aircraft cleaning system called NOC.

The alternative cleaning solvent chosen for this project as a replacement for chlorofluorocarbons (specifically CFC-113) and hydrochlorofluorocarbons (specifically HCFC-141b) is methoxy-nonafluorobutane (C<sub>4</sub>F<sub>9</sub>OHC<sub>3</sub>) manufactured by 3M<sup>TM</sup> under the product name HFE-7100. HFE-7100 is a clear, colorless and low-odor fluid and is an acceptable substitute for ozone depleting substances in specific solvent cleaning and aerosol industry applications under its Significant New Alternatives Program (SNAP). HFE-7100 is officially listed as a non-volatile organic compound (VOC) by the Environmental Protection Agency (EPA) (per the 8/25/97 Federal Register). Environmental properties compared to the baseline cleaners are listed in Table 10.

**Table 10. Environmental Properties<sup>a</sup>**

<b>Property</b>	<b>3M<sup>TM</sup> HFE-7100</b>	<b>CFC-113</b>	<b>HCFC-141b</b>
Ozone Depletion Potential <sup>b</sup> -ODP	0.00	0.80	0.10
Global Warming Potential <sup>c</sup> - GWP	480	5000	630
Atmospheric Lifetime – ALT (yrs)	4.1	8.5	9.4

<sup>a</sup> Source 3M<sup>TM</sup> HFE-7100 Product Information Sheet

<sup>b</sup> CFC-11 = 1.0

<sup>c</sup> GWP – 100 year Integration Time Horizon (ITH)

Onboard demonstration/validation (dem/val) was performed at OC-ALC, OK; WR-ALC, GA; Tulsa ANG, Tulsa, OK; and Kentucky ANG, Louisville, KY. Photographs of the equipment used in this process are provided in Appendix A.

Off-aircraft dem/val was performed by Northrop Grumman and NAVAIR. A description of the equipment and procedures used in these processes are included in Appendix A.

## 4.0 TEST RESULTS

This section of the JTR gives a brief rationale and objective for each test (reference the JTP for additional information), the results of the testing, and specifies whether the test results met the acceptance criteria set by the technical representatives of the JG-PP project team.

### 4.1 Onboard Cleaning

This section contains the critical requirements for qualifying the non-ozone depleting cleaner for onboard aerospace vehicle cleaning (i.e., cleaning in place). Dem/val was performed on the B-1 aircraft at Tinker AFB, on the F-15 at Robins AFB, and on the F-16 at the Oklahoma ANG, Tulsa ANG Base. Versar, Inc. conducted all demonstrations that were witnessed by Government personnel.

#### 4.1.1 LOX Impact

LOX impact testing was completed before additional testing was initiated to ensure that the proposed cleaning solution does not initiate or propagate an explosion or fire in an oxygen-rich environment (liquid or gas). This test was initially performed on neat HFE-7100 to certify that the base solvent (solvent with no surfactant) is compatible with an oxygen-rich environment when a specific amount of impact energy is imparted on it.

Pure HFE-7100 was tested, as required by the JTP. LOX impact testing of the solvent was conducted using liquid oxygen at ambient pressure.

The JTP acceptance criterion is that there be zero reactions (explosion, flash, burning, major discoloration, temperature or pressure spike) for 20 successive impacts at 98 joule (J) (72 foot-pounds of force (ft-lb<sub>f</sub>)). Test results are given in Table 11. The HFE-7100 solvent met the acceptance criteria. The full LOX compatibility test report is located in Appendix B.

**Table 11. LOX Test Results**

<b>Impact Energy</b> J ([ft-lb])	<b>Pressure</b>	<b>Number of</b> <b>Reactions</b>	<b>Number of Samples</b> <b>Impacted</b>
98 (72)	Ambient	0	20

The HFE-7100 was also subjected to a high-pressure autogenous ignition test. The solvent was tested three times in 100 percent oxygen at an initial pressure of approximately 345 kPa (50 psia) and three times in 100 percent oxygen at an initial pressure of approximately 13.8 MPa (2000 psia). The average sample weight for each test was  $0.22 \pm 0.01$  g. The starting temperature for each test was 60°C (140°F) per ASTM G72-82. The heating rate in the reaction vessel was  $5 \pm 1^\circ\text{C}$  ( $9 \pm 2^\circ\text{F}$ ) per minute for the entire heating range. The maximum temperature of the reaction vessel was set at 450°C (842°F).

No ignition event was detected for the test conducted at 345kPa (50 psia) or 13.8 MPa (2000 psia). An ignition event is indicated by a rapid temperature rise of at least 20°C (36°F). However, a small sub-threshold exothermic reaction was observed for all samples tested at 13.8 MPa at 399°C (750°F). The posttest residue for all tests appeared as a white powder deposited on the inside of the test tubes.

As described in Section 2.1.2.1, LOX compatibility testing was also conducted with 0.10 wt.% Krytox Alcohol (surfactant) in HFE 7100. The surfactant/solvent mixture failed LOX impact testing at ambient pressure - results of this additional testing are given in Table 12 below. During testing, a visually detected flash was present, as well as charring, which indicated burning. The complete test report is located in Appendix B.

LOX impact testing sets the baseline for use and failures do not necessarily result in unacceptable applications. This testing indicates that, should surfactant be used to enhance cleaning, care must be taken to assure all traces of surfactant are removed before the aircraft returns to service. Subsequent testing processes must provide this assurance. The process developed for line cleaning does not require surfactant for all current applications.

**Table 12. LOX Test Results for surfactant/solvent mixture**

<b>Impact Energy (J) {(ft-lb)}</b>	<b>Pressure</b>	<b>Number of Reactions</b>	<b>Number of Samples Impacted</b>
98 {72}	Ambient	2	3

#### **4.1.2 Material Compatibility**

The material compatibility test ensures that no system components are damaged due to the cleaning process. This requirement is an accepted industry standard per ASTM G127 (*Standard Guide for the Selection of Cleaning Agents for Oxygen Systems*, approved June 15, 1995). The test procedure was performed three times to simulate three lifetime phased depot maintenance (PDM) refurbishing cycles.

This test exposes the available materials to the test solvent/surfactant mixture. A 0.05 wt% Krytox Alcohol in HFE-7100 mixture was prepared for this test. Some samples of an identical material had very different forms and “impurities,” which may include dyes, plasticizers, and other additives; so multiple samples of these materials were used to test the different physical characteristics (e.g., thin white diaphragm vs. orange disc, both of which were silicone rubber). The exposure time for each material during a line cleaning process is no more than one hour. Therefore, each sample was exposed to the solvent/surfactant mixture for one hour for each of the three samples. This is considered to be equivalent to the maximum lifetime exposure. Details of the test procedure are located in Appendix C.

The acceptance criterion upon completion of testing is that there be no visible or permanent evidence of substrate deterioration. ASTM G 127-95 states that changes to non-metallic materials “are typically characterized by swelling, distortion, cracking, crazing, blistering, embrittlement and decomposition temperature shift....refer to Test Methods D 471, D 543, D 1460, and Practice D 2934.”

All samples were weighed both before and after each exposure. The samples were visually inspected to determine if any obvious change occurred. Since there was no visible or permanent evidence of substrate deterioration for any samples, based on the criteria listed above (visible swelling, distortion, etc.), HFE-7100 passed the test requirements for each tested material. Table 13 gives the results of the weight change for the material compatibility samples. However, since no  $\pm$  wt% acceptance criterion was provided in the JTP or ASTM G127-95 for this test, this data is given for information only.

**Table 13. Material Compatibility Sample Weights**

Material	Sample Description	Sample Number	Weight Before (grams)	Trial Number	Weight After (grams)	Difference (grams)
Silicon Rubber	White Thin Diaphragm	1.1	0.4714	1	0.4535	0.0179
				2	0.4501	0.0213
				3	0.4484	0.0230
Silicone Rubber	Orange Disc	1.3	0.3721	1	0.3230	0.0491
				2	0.3215	0.0506
				3	0.3209	0.0512
Silicone Rubber	Light Gray Seal - Cone Shape	1.4	0.2522	1	0.2524	-0.0002
				2	0.2524	-0.0002
				3	0.2524	-0.0002
Nylon	White Tube	6.1	0.6956	1	0.6956	0.0000
				2	0.6953	0.0003
				3	0.6952	0.0004
Teflon	White Anti-Seize Tape	7.1	0.9569	1	0.9568	0.0001
				2	0.9570	-0.0001
				3	0.9569	0.0000
Teflon	Silver Stainless Steel Tape	7.2	0.9425	1	0.9425	0.0000
				2	0.9426	-0.0001
				3	0.9424	0.0001
Teflon	Small White Seal	7.3	0.2510	1	0.2510	0.0000
				2	0.2510	0.0000
				3	0.2509	0.0001
Teflon	Semi opaque washer	7.4.1	0.0730	1	warped during drying	
Teflon	Semi opaque washer	7.4	0.0674	1	0.0674	0.0000
				2	0.0674	0.0000
				3	0.0675	-0.0001

**Table 13. Material Compatibility Sample Weights (Continued)**

<b>Material</b>	<b>Sample Description</b>	<b>Sample Number</b>	<b>Weight Before (grams)</b>	<b>Trial Number</b>	<b>Weight After (grams)</b>	<b>Difference (grams)</b>
Polysulfone	Amber Plastic Disk	8.1	0.6583	1	0.6579	0.0004
				2	0.6574	0.0009
				3	0.6573	0.0010
CycloLak (DuPont)	Hard Black Tube	9.1	2.4775	1	2.4766	0.0009
				2	2.4763	0.0012
				3	2.4762	0.0013
Nitril Rubber	Blue Rubber Glove	11.1	0.9567	1	0.9543	0.0024
				2	0.9539	0.0028
				3	0.9528	0.0039
Polycarbonate	Hard Black Cockpit Particle	12.1	0.3035	1	0.3028	0.0007
				2	0.3023	0.0012
				3	0.3026	0.0009
Polyvinyl Chloride (PVC)	Green Plug	13.1-2	0.3737	1	deformed during drying	
Polyvinyl Chloride (PVC)	Light Green Cap	13.1	0.3398	1	0.3399	-0.0001
				2	0.3400	-0.0002
				3	0.3401	-0.0003
Viton (Fluoro Elastomer)	Valve with Viton Seal	14.1	0.1747	1	0.1717	0.0030
				2	0.1718	0.0029
				3	0.1720	0.0027
Viton (Fluoro Elastomer)	Valve with Viton Seal	14.2	0.2525	1	0.2516	0.0009
				2	0.2519	0.0006
				3	0.2520	0.0005
Electrical Wire Insulation	Red Electric Wire	15.1	0.1813	1	0.1810	0.0003
				2	0.1810	0.0003
				3	0.1812	0.0001
Cockpit Plastic Particle	Black with Silver and Test Mark Imprint	16.1	0.8870	1	0.8869	0.0001
				2	0.8869	0.0001
				3	0.8870	0.0000
Cockpit Plastic Particle	Clear V-shaped arc of plastic	16.2	0.4657	1	0.4656	0.0001
				2	0.4657	0.0000
				3	0.4656	0.0001

Photographs of the material compatibility samples are given in Appendix C. Also located in that appendix is a further description of the samples tested and the corresponding equipment component.

GC chromatograms were obtained for the original Krytox Alcohol/HFE-7100 mixture, and the solutions from the first exposure of the samples that showed the highest weight loss (Sample 1.1) and the smallest weight loss (Sample 7.3). Chromatograms are available in Appendix C. GC testing did not produce any discernable results. The

purpose of the GC testing was to identify individual peaks associated with the solvent and surfactant. Any additional peaks would indicate leachate remaining after solvent exposure. However, the available chromatograms show numerous peaks representing a number of various chemical species that cannot be easily identified or quantified using gas chromatography. Also, the relative sizes of the peaks provide minimal insight into the effect of soaking each material in the solvent/surfactant mixture. Therefore, GC testing was not completed on all the material compatibility samples.

#### 4.1.3 Nonvolatile Residue

The objective of this test is to provide a qualitative determination of how well the oxygen lines were cleaned by using a relative comparison of the NVR weights before and after cleaning. The JTP specifies that the testing be completed per ASTM F331, *Standard Test Method for Nonvolatile Residue of Solvent Extract from Aerospace Components (Using Flash Evaporator)*, approved October 10, 1998. This test is intended to show that if the weights of NVR applied to a test coupon before cleaning is comparatively the same as the weight of NVR collected in the inline filter(s) and the wash solution after cleaning, it is assumed that the cleaning process has removed the NVRs and carried them to the collection vessel and inline filter. However, as stated in Section 2.1.2.3, this test method could not be effectively used with the OLCs. Therefore, Versar devised a different test method; a description of the test procedure is located in Appendix D.

The results obtained for the contaminants tested by Versar, are summarized in Table 14.

**Table 14. NVR Test Results**

		Test Cell	Coupon Weights			
			Before	After	After	
Contaminant	Trial #	Size (OD) (inches)	Contamination (g)	Contamination (g)	Cleaning (g)	% Clean
MIL-H-5606	1	3/8	0.5110	0.5379	0.5120	96.28%
	2	3/8	0.5131	0.5533	0.5133	99.50%
Amberlube EC-98	1	3/8	0.5198	0.5963	0.5211	98.30%
	2	3/8	0.4984	0.5533	0.4989	99.09%
MS-139	1	3/8	0.5110	0.5915	0.5114	99.50%
	2	3/8	0.5131	0.6095	0.5133	99.79%
25i Blue Wave	1	3/8	0.5198	0.5537	0.5214	95.28%
	2	3/8	0.4984	0.5231	0.5022	84.62%

**Table 14. NVR Test Results (Continued)**

		Test Cell	Coupon Weights			
			Before	After	After	
Contaminant	Trial #	Size (OD)	Contamination	Contamination	Cleaning	% Clean
MIL-PRF-7808	1	3/8	0.5110	0.553	0.5112	99.52%
	2	3/8	0.5131	0.5467	0.5131	100.00%
WD-40	1	3/8	0.5198	0.5394	0.5201	98.47%
	2	3/8	0.4984	0.5120	0.4984	100.00%
Krytox Grease	1	3/8	0.5110	0.6901	0.5112	99.89%
	2	3/8	0.5131	0.8754	0.5133	99.94%

#### 4.1.4 Moisture

This test determines the moisture content of the cleaning solvent that is to be used for testing. The solvent is to be tested as received and the moisture content measured in ppm. The test must be run once for the entire drum, but may be run multiple times to certify the drum material.

The manufacturer Commercial Item Description (CID) specifies that the solvent must have no more than 100 ppm of water. Based on technical advice, an acceptance criterion of 60 ppm of water was set for this JTP. This solvent certification was accomplished in accordance with ASTM D5530-94 to fulfill the requirements of CID A-A-59150A as stipulated in the JTP.

Versar received results from moisture tests performed by the manufacturer on the two most recently received drums of solvent. They were certified in accordance with CID A-A-59150A meeting the specified acceptance criteria. The results are given in Table 15.

**Table 15. Moisture Test Results**

HFE-7100 Lot Number	Moisture Content
24022	8 ppm
24035	7 ppm

#### 4.1.5 Cleanliness Verification

The objective of this test is to determine the cleanliness level of a test article by determining particle counts, NVR, and surface particulate verification using a SEM. This requirement is an accepted industry standard per ASTM G93 and F312. The test procedure used did not follow these procedures for reasons described in Section 2.1.2.4.

Test results from the modified procedure are given in Table 16. Complete test results and photographs are given in Appendix E.

**Table 16. Summary of Cleanliness Verification Results**

		Test Cell	Coupon Weights				Wash	
			Before	After	After		Flow	
			Cont.	Cont.	Cleaning		Time	Velocity
Contaminants	Trial	Size (OD) (inches)	(g)	(g)	(g)	% Clean	(min.)	(ft/sec)
WD 40 & ARD	1	3/8	0.5131	0.5551	0.5134	99.29%	4	15.0
Amberlube & ARD	1	3/8	0.5131	0.6642	0.5164	97.82%	4	15.1
	2	3/8	0.5196	0.6393	0.5227	97.41%	4	15.0
MIL-PRF-7808 & ARD	1	3/8	0.5110	0.6203	0.5112	99.82%	4	15.1
	2	3/8	0.5131	0.5926	0.5133	99.75%	4	15.0
MIL H 5606 & ARD	1	3/8	0.5110	0.6106	0.5348	76.10%	4	14.9
	2	3/8	0.5131	0.6709	0.5369	84.92%	4	15.1
	3	3/8	0.5110	0.5954	0.5215	87.56%	4	15.1
	4	3/8	0.5131	0.6116	0.5267	86.19%	4	15.0
	5	3/8	0.5110	0.6825	0.5197	94.93%	10	18.0
	6	3/8	0.5131	0.6699	0.5248	92.54%	10	18.1
MS 139 & ARD	1	3/8	0.5198	0.6819	0.5234	97.78%	4	15.0
	2	3/8	0.4984	0.6802	0.5013	98.40%	4	15.1
25i Blue Wave & ARD	1	3/8	0.5110	0.6179	0.5154	95.88%	4	15.0
	2	3/8	0.5131	0.6288	0.5178	95.94%	4	14.8
Kryton Grs. & ARD	1	3/8	0.5198	0.7742	0.5203	99.80%	4	14.9
	2	3/8	0.4984	0.7000	0.4986	99.90%	4	14.9
Dist. Water & ARD	1	3/8	0.5110	0.6399	0.5136	97.98%	4	14.6
	2	3/8	0.5131	0.6328	0.5148	98.58%	4	14.8
Acetone & ARD	1	3/8	0.5198	0.5961	0.5199	99.87%	4	15.1
	2	3/8	0.4984	0.5638	0.4984	100.00%	4	14.9

#### 4.1.6 Functional Test

The purpose of the functional testing was to determine that the aircraft's oxygen system functioned properly after cleaning. The acceptance criteria states that the system be functional and the operation not be impaired by the cleaning process. The JTP also requires that no odor be detected.

In order to clean an aircraft, the oxygen storage or production equipment must be removed. This is the point of input to the oxygen system for the cleaning process. The regulators, or other devices, at the termination of a branch of the oxygen system are removed so that return connections can be made. This provides a closed loop system that

results in all internal surfaces of the oxygen plumbing being wetted with solvent. The only components left in the system are pressure transducers, flow sensors, relief valves, check valves and shut off valves; however, not all aircraft will have all these components. These components were verified to function following the aircraft cleaning demonstrations and individually as a natural consequence during the development effort.

After demonstrating the OLCS on a portion of the oxygen lines on a C-130 aircraft, the LOX converter was charged, regulators were re-installed and masks were connected to the regulators. Government representatives breathed through the masks for several minutes to test the quality of the oxygen flowing through the lines that were cleaned. No noticeable odors were detected.

#### **4.1.7 Component/Model/System Replica Test**

The purpose of this test is to verify the capability of the cleaning process on a B-1 mock-up oxygen line system prior to actual platform testing.

The line cleaning process was performed numerous times on the B-1 mock-up located at the Versar office in Oklahoma City, OK. The mock-up was inspected by a government representative, and the process was approved for use on actual aircraft.

System testing was conducted on the B-1, F-15, F-16, and C-130 aircraft. Tinker AFB, personnel approved the test and demonstration of the OLCS on an actual B-1B aircraft (tail no. 054) on November 3, 2001. The 138<sup>th</sup> FW, Oklahoma ANG, Tulsa ANG Base approved the test/demo the OLCS on an F-16 aircraft on November 20, 2001. Robins AFB personnel approved the test/demo cleaning of a single seated F-15 aircraft for December 12, 2001. Kentucky ANG 123d AMW, personnel approved the test and demonstration of the OLCS on a C-130 aircraft on June 5, 2002.

Appendix F contains the test/demo reports, lab reports and photographs of the equipment for each aircraft.

#### **4.1.8 Dead Areas**

As stated in Section 2.1.2.6, the procedure used by Versar for the dead areas test varied from the test procedure stated in the JTP due to the fact that no surfactant was used in conjunction with the HFE-7100. All test procedures referenced below are located in Appendix G.

Versar initiated their test procedures by testing the sensitivity of the halide detector to quantities of HFE-7100 in the dry air purge stream. The dry airflow rate had to be high enough to maintain a reasonably low residence time in the tubing, and low enough to allow the HFE-7100 to diffuse into the dry air stream at a reasonable rate. A dry airflow rate of 2.5 liters/minute (L/min) was used for these tests

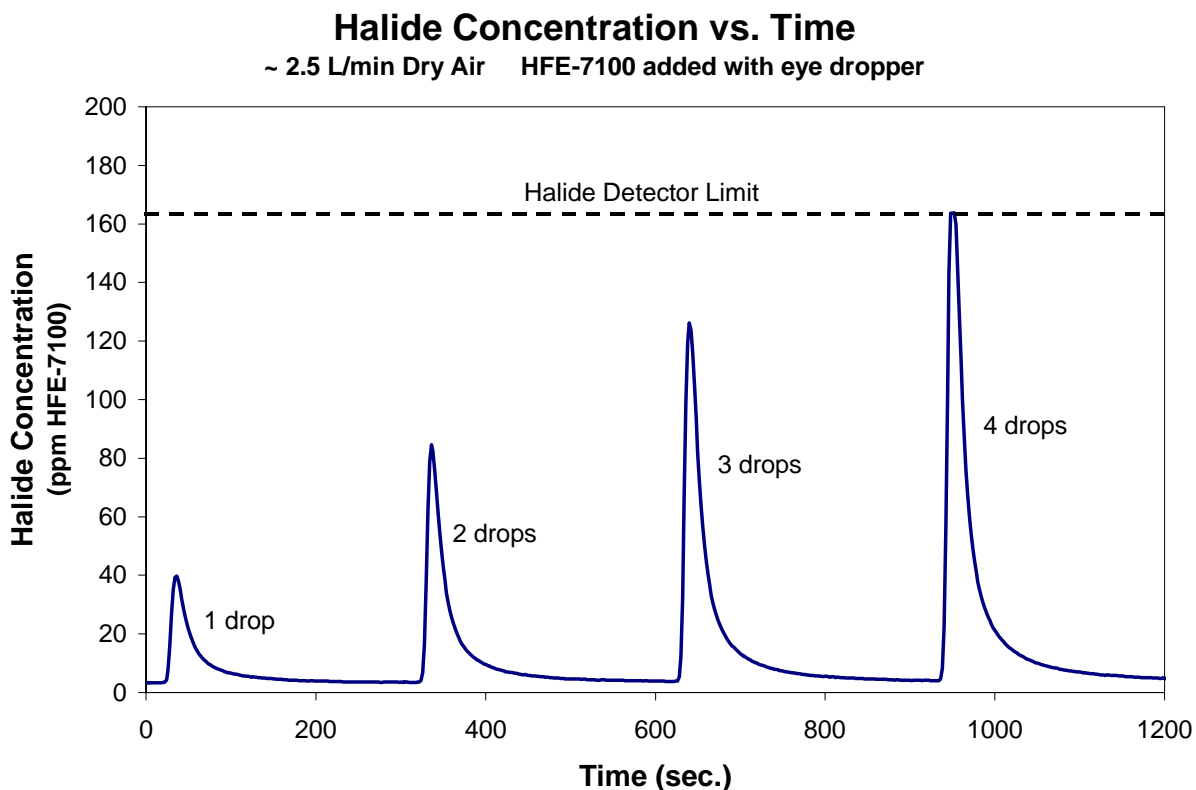
A dry air purge of 2.5 L/min is significantly lower than the resting respiratory rate of an adult. This means that halide concentrations detected using a dry air purge rate of 2.5 L/min would be equal to, or greater than, those experienced by the crew breathing

from the end of the tubing. That is, the halide detector reading would be the absolute maximum concentration of HFE-7100 that an aircrew member would encounter.

The Drop Test determined how well the halide detector sensed HFE-7100 present within the direct flow path of the dry air purge. Prior calibration of the detector indicated that the maximum concentration of HFE-7100 in air that can be quantified by the halide detector is 166 ppm. The JTP suggests that the end concentration of solvent in the aircraft tubing be continuously below 600 ppm. The halide detector cannot quantify concentrations that high. Therefore the acceptance criteria must be modified.

An HFE-7100 MSDS dated January 13, 2000, states that the time weighted average (TWA) exposure limit for the two isomers composing HFE-7100 is 750 ppm each. In order to ensure that no crewmember would ever be exposed to solvent concentrations approaching this level, a maximum solvent concentration of 40 ppm was established as the acceptance criteria.

As Figure 1 shows, the halide detector is very sensitive to small quantities of HFE-7100 present in a direct flow-path within the tubing. HFE-7100 concentrations quickly stabilized below 3 ppm after the drops of HFE-7100 had been evaporated and purged from the system.

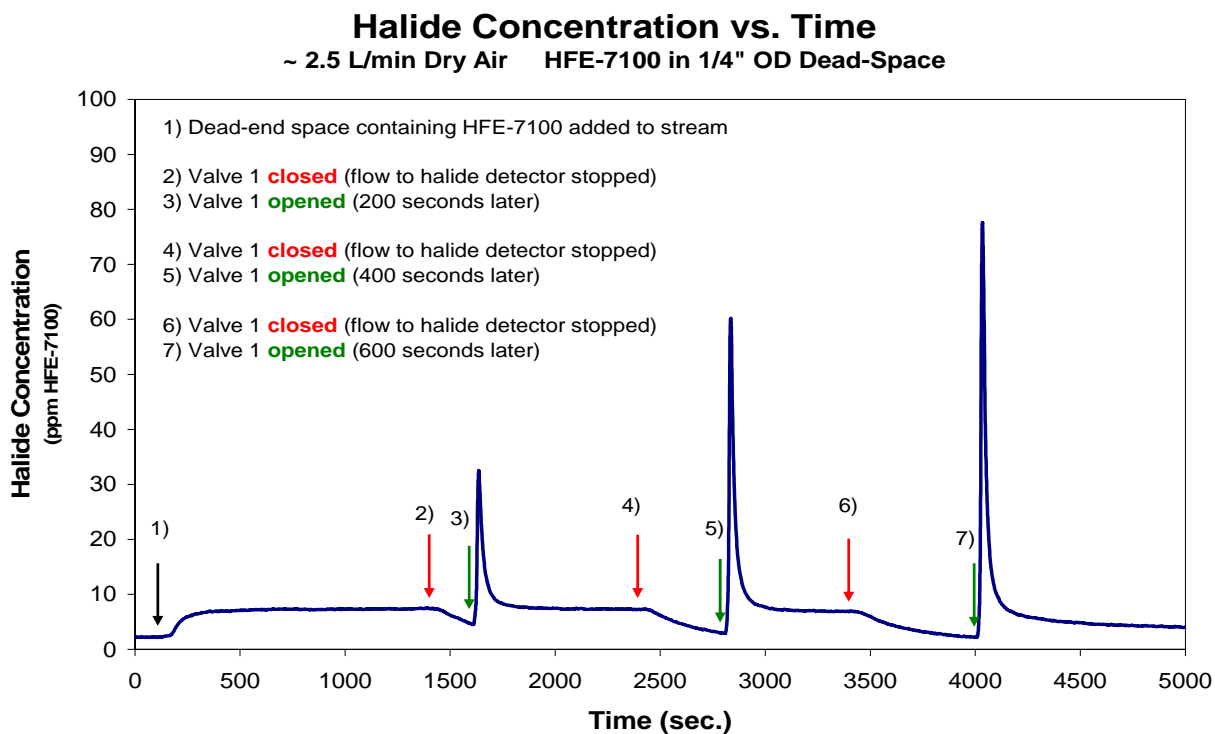


**Figure 1. Drop Test Results**

The Dead-Space Test determined how well the halide detector sensed HFE-7100 present within a dead space in the tubing, that is, solvent not directly within the flow path of the

dry air purge. As Figure 2 shows, the diffusion rate of the HFE-7100 in the dead-space into the dry air purge flow was too low to provide a significant increase in the halide concentration reading from the halide detector. The halide detector reading increased from about 2 ppm to 7 ppm after the dead space containing HFE-7100 was added to the test stand.

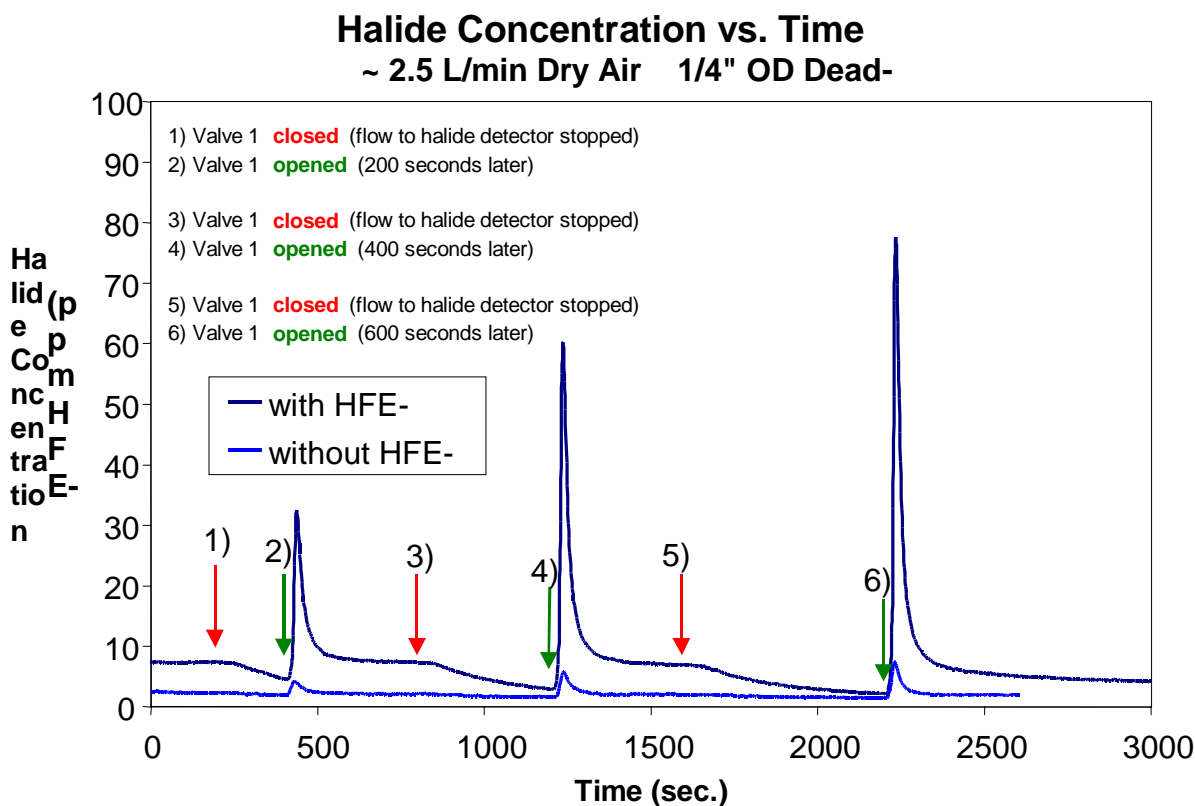
When the purge air stream is stopped, HFE-7100 slowly evaporates from the dead-space until the tubing volume is saturated with solvent vapor. When the dry air purge flow is reinitiated, the halide detector is hit with a quick “slug” of air containing relatively high concentrations of HFE-7100. These slugs are quickly purged from the lines, and the halide concentration returns to its normal steady-state value.



**Figure 2. Dead Space Test Results**

The Dead-Space Purge and Test shows how well the vacuum purge removes HFE-7100 from the dead areas in the system (see Figure 3). The halide concentration in the dry air purge is considerably lower after the vacuum purge.

After the halide detector testing, the dead-space was removed and visually inspected. No trace of HFE-7100 was present in the dead-space volume after evacuation.



**Figure 3. Dead-Space Purge and Test Results**

From these test results the following information can be ascertained:

- Any significant quantity of liquid HFE-7100 present within the dry airflow path produced relatively large halide concentration values on the halide detector (> 100 ppm)
- The evaporation and diffusion rates of HFE-7100 in a dead space are too low at ambient conditions to produce a halide concentration greater than ~ 10 ppm on the halide detector for continuous dry airflow rates greater than ~2.5 L/min dry airflow rate
- The dry air purge must be used in conjunction with the vacuum purge to assure that no HFE-7100 remains in the aircraft after the wash and rinse cycles of the cleaning procedure.

#### 4.1.9 Leak Testing

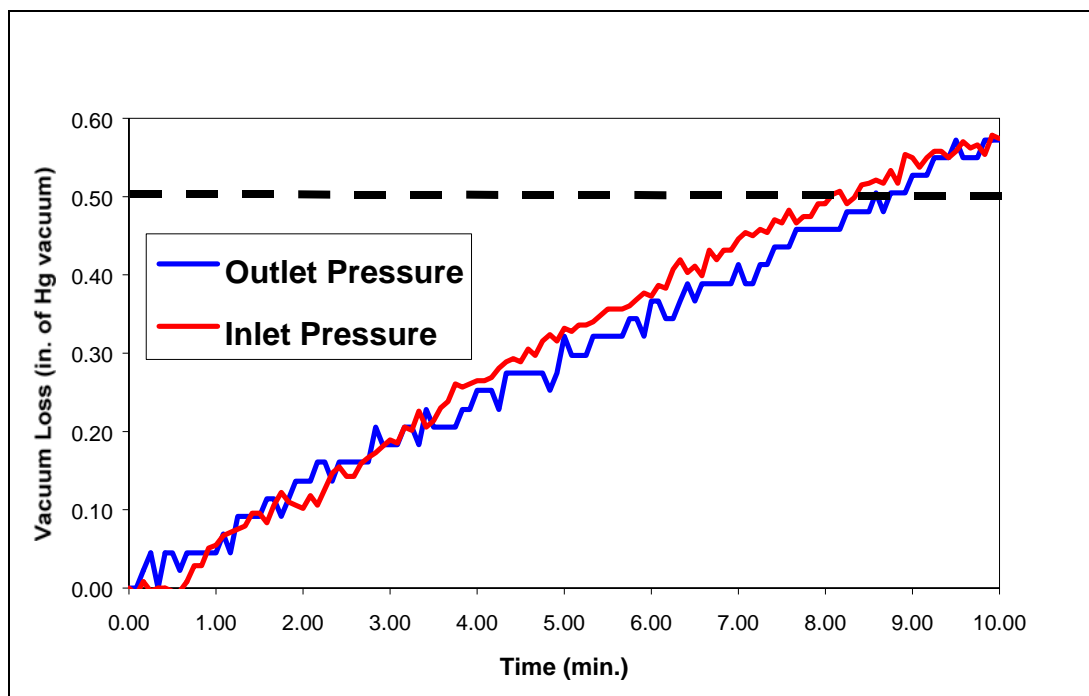
This test ensures that no significant leaks are present in the oxygen line system. This procedure helps prevent the loss of cleaning fluid and other fluid loss related problems (electrical and mechanical on board the aircraft). It is performed on the oxygen line system to determine whether or not the system exceeds the acceptable loss criteria for the oxygen line-cleaning device (criteria is set for each platform by the military). Leak testing takes place before the cleaning process begins to ensure that the level of leaking is

in accordance with set Government standards and regulations. A detailed description of the leak testing procedure is given in Appendix H.

During testing on the B-1 mock-up, the pressure in the system was lowered to just below 28 in. Hg (Inches of mercury) vacuum. The pressure increased 0.57 in. Hg over the next ten minutes. The results are shown in Figure 4; actual data is located in Appendix H. This exceeded the 0.50 in. Hg limit originally established in the Versar Test Plan. Each fitting on the system was examined and tightened (if necessary). This did not significantly improve the leak rate of the system. The OLCS was operated under normal conditions (fluid pressures up to 200 psia) and no leaks were detected under close observation. It was decided that for the B-1B mock-up, the leak rate tolerance could be set higher – at least as high as 0.75 in. Hg vacuum loss over ten minutes – and still prevent solvent loss.

The OLCS unit uses a high-pressure leak test to determine the potential loss of solvent in an aircraft. The inlet lines, aircraft lines, and return lines, are pressurized to 60 psig. A leak rate less than 0.30 pounds per square inch per minute (psi/min) at this pressure prevents solvent loss. The average leak rate for the pressure test on the B-1 mock-up is 0.18 psi/min.

A graph illustrating the vacuum loss, as a function of time, is given in Figure 4.



**Figure 4. Vacuum Loss vs. Time**

#### **4.1.10 Hazard Analysis**

This test provides the user with the acceptable operating limits in association with the oxygen line cleaning device. The focus of the hazard analysis investigation is to collect information on the components and the worst-case operating condition. Prior to the completion of the OLCS prototype, an 85% design review was conducted, whereby representatives from both commercial and government organizations were able to observe the operation of OLCS and comment on its function. Also, careful consideration was given to any hazards or dangerous conditions that may exist while the OLCS is cleaning aircraft plumbing. The comments and suggestions that were made by the group were used when finalizing the safety precautions and failsafe mechanisms on the completed OLCS prototype.

In considering the risk for fire and/or explosion when using a solvent in an oxygen rich environment, extensive testing has been performed on HFE-7100, the cleaning solvent used in the OLCS. These tests proved that HFE-7100 is non-explosive in a pure oxygen environment and is unable to sustain a fire under normal operating conditions.

#### **4.2 Off-Aircraft Oxygen Line Cleaning**

This section contains the critical requirements for qualifying the non-ozone depleting cleaner for off-aircraft aerospace vehicle cleaning (i.e., cleaning in place). Two systems were evaluated during this analysis. A system using the non-ozone depleting cleaner was tested by Northrop Grumman, and an aqueous system called the Navy Oxygen Cleaner process was tested by NAVAIR. Soil removal testing was conducted on the Northrop Grumman cleaning system, and NVR and Particle Count were conducted on the NOC.

##### **4.2.1 Nonvolatile Residue**

This test will determine the amount of all types of NVR washed out of an oxygen system or component after cleaning and rinsing, per MIL-STD-1330D, *Standard Practice for Precision Cleaning and Testing of Shipboard Oxygen, Helium, Helium-Oxygen, Nitrogen, and Hydrogen Systems*, issued September 20, 1996. Oxygen tubes were artificially soiled in the laboratory in accordance with ASTM G121-98. The amount of contaminant was determined, the samples were cleaned using the NOC System or the Northrop/Grumman System and the amount of contaminant remaining after cleaning was measured. Different substrates, contaminants and line sizes were given in the JTP to be tested.

Acceptance criteria are given in Table 17 below.

**Table 17. NVR Acceptance Criteria**

<b>Programs Requiring Tests</b>	<b>Acceptance Criteria (ppm by weight)</b>
Navy (NOC process)	5 (maximum NVR above baseline in final NOC cleaner)
Air Force/B-1, NASA	9.3 (maximum NVR above baseline in final NOC cleaner)
Northrop Grumman	See T.O. 15-X-1-1

As stated in Section 2.2.2.1, only NAVAIR submitted test results for NVR Testing. Therefore, the acceptance criterion to be used on these samples is that listed for the NOC process in Table 17 above. NAVAIR tested thirty-six samples and all met the acceptance criteria. Test Results are given in Table 18 below.

**Table 18. NVR Testing Sample Results for Navy  
Oxygen Cleaning System – Off-aircraft**

<b>Alloy</b>	<b>Contaminant</b>	<b>Line Size</b>	<b>Sample Number</b>	<b>PPM Contaminant After Cleaning<sup>a</sup></b>	<b>% Removal</b>
<b>Copper (Pure)</b>	WD-40 Lubricant	5/16" OD 2ft Long	AC0041	0	100
		5/16" OD 4ft Long	1006995	0	100
		5/16" OD 6ft Long	AC0042	0	100
	Krytox 240 AB	5/16" OD 2ft Long	915994	0	100
		5/16" OD 4ft Long	929994	0	100
		5/16" OD 6ft Long	517001	0	100
	Oakite Drawsyn	5/16" OD 2ft Long	AC0043	0	100
		5/16" OD 4ft Long	915996	0	100
		5/16" OD 6ft Long	AC0044	0	100
	Hydraulic Fluid	5/16" OD 2ft Long	AC0045	0	100
		5/16" OD 4ft Long	915992	0	100
		5/16" OD 6ft Long	915995	0	100
<b>Stainless Steel</b>	WD-40 Lubricant	5/16" OD 2ft Long	10069910	0	100
		5/16" OD 4ft Long	AC0046	0	100
		5/16" OD 6ft Long	AC0047	0	100
	Krytox 240 AB	5/16" OD 2ft Long	929991	0	100
		5/16" OD 4ft Long	929993	0	100
		5/16" OD 6ft Long	517001	0	100
	Oakite Drawsyn	5/16" OD 2ft Long	1006996	0	100
		5/16" OD 4ft Long	914996	0	100
		5/16" OD 6ft Long	AC0048	0	100
	Hydraulic Fluid	5/16" OD 2ft Long	1006998	0	100
		5/16" OD 4ft Long	1006999	0	100
		5/16" OD 6ft Long	AC0049	0	100

**Table 18 NVR Testing Sample Results for Navy  
Oxygen Cleaning System – Off-aircraft (Continued)**

<b>Alloy</b>	<b>Contaminant</b>	<b>Line Size</b>	<b>Sample Number</b>	<b>PPM Contaminant After Cleaning<sup>a</sup></b>	<b>% Removal</b>
<b>Aluminum 6051 T6</b>	WD-40 Lubricant	5/16" OD 2ft Long	909994	0	100
		5/16" OD 4ft Long	909995	0	100
		5/16" OD 6ft Long	AC0050	0	100
	Krytox 240 AB	5/16" OD 2ft Long	929992	0	100
		5/16" OD 4ft Long	517002	0	100
		5/16" OD 6ft Long	517003	0	100
	Oakite Drawsyn	5/16" OD 2ft Long	AC0051	0	100
		5/16" OD 4ft Long	AC0052	0	100
		5/16" OD 6ft Long	AC0053	0	100
	Hydraulic Fluid	5/16" OD 2ft Long	AC0054	0	100
		5/16" OD 4ft Long	AC0055	0	100
		5/16" OD 6ft Long	AC0056	0	100

<sup>a</sup> 5 ppm by weight max

#### **4.2.2 Soil Removal**

This test will determine the ability of a specific agent/process to remove selected contaminants to the desired level. Oxygen tubes were artificially soiled in the laboratory in accordance with ASTM G121. The amount of contaminant was determined, the samples were cleaned using the Northrop Grumman system, and the amount of contaminant remaining after cleaning was measured. Different substrates, contaminants and line sizes were given in the JTP.

The acceptance criterion is that the Cleaning Effectiveness Factor (CEF) must be greater than that stated in Technical Order 15-X-1. However, the CEF was not provided and it is not known whether these test results meet the Technical Order requirements.

Table 19 gives the soil removal test results. Photographs of the test jig used, actual test samples before, with contamination and after cleaning, are located in Appendix I.

**Table 19. Soil Removal Test Results**

Testing Date	Coupon #	Size/Stream	Contaminant	Time (minutes)	Flow (gpm)	Weight Before	Weight with Contaminant	Weight After Cleaning	Results (%)
7-25-01	1.5	½" Straight	ARD & Distilled Water	20	4	0.8007	0.8349	0.8053	86.55
7-25-01	2.0	½" Straight	ARD & Krytox Grease	20	4	0.7923	1.0551	0.7931	99.70
7-26-01	9.0	5/8" Curved	ARD & Distilled Water	20	4	1.0377	1.0924	1.0918	1.10
7-26-01	9.0	5/8" Curved	ARD & Krytox Grease	20	4	1.0377	1.3395	1.0379	99.93

#### 4.2.3 Particle Count

This test indirectly evaluates the cleanliness of a test article by counting the number of particles observed in a sample of the nitrogen purge stream that is used following the solvent cleaning step. The low particle count (Level 50, as shown in Table 1 of MIL-STD-1246C) is required by NAVAIR due to higher pressures and purer oxygen used in aircraft lines.

Acceptance criteria are given in Table 20. The complete test report is located in Appendix J.

**Table 20. Particle Count Acceptance Criteria**

Level 50, as follows (particle count per liter)	
< 10 µm	unlimited
15-25 µm	17
25-50 µm	8
> 50 µm	0

1 sample = 3 liters<sub>MIN</sub> of final N<sub>2</sub> purge as per JPG 5322.1 Rev. E Note 4

One sample was tested and met the acceptance criteria. Results are given in Table 21.

**Table21. Particle Count Test Results  
(Sample: Purge N2 from O2 Lab)**

(Particle count per liter) $\mu\text{m}$	(Particle count per liter) $\mu\text{m}$
0-5	24
5-10	3
10-15	0
15-20	0
20-25	0
25-30	0
30-50	0
50-100	0

#### **4.2.4 Water Content**

The objective of this test is to identify the ppm of moisture in the particles in the nitrogen purge stream that is used following the solvent cleaning step. The test is required to prevent icing and corrosion of oxygen systems onboard aircraft.

As stated in Section 2.2.2.3, this test was not completed.

## 5.0 SUMMARY AND RECOMMENDATIONS

This section summarizes the testing results of the two alternative technologies evaluated for this project: an alternative zero ozone depleting cleaning solvent (HFE-7100) and an aqueous cleaning system. Two methods of cleaning were also tested for qualification: onboard aerospace vehicle cleaning (i.e., cleaning in place) and off-aircraft cleaning.

The alternative cleaning solvent tested onboard used equipment provided by Versar and the solvent tested off-aircraft used equipment provided by Northrop Grumman. In addition, an aqueous cleaner was tested using an off-aircraft cleaning system called the NOC Process.

Only several of the tests were carried out as specified in the JTP and met the acceptance criteria. These tests include moisture testing for onboard cleaning and particle count testing for off-aircraft cleaning. In addition, nonvolatile testing for the off-aircraft testing was conducted and passed the acceptance criteria, but only on the NOC system; no testing was conducted on the Northrop Grumman system. The results of all these tests passed the JTP acceptance criteria, indicating that the solvents and selected cleaning methods were sufficient for cleaning the oxygen lines.

Numerous modifications to the JTP were made during the testing of the onboard cleaning system. When this program was chosen to become a joint program requiring a JTP, test parameters and procedures were specified to meet all requirements of the various organizations. These tests were derived from engineering, performance, and operational impact requirements defined by a consensus of government and industry participants. These testing requirements are identified in the JTP. In executing some of the tests, deviations from the described procedure became necessary to accomplish the intended goal. These modifications were described in detail in Section 2.1.2.

Pure HFE-7100 was LOX impact tested, per an alternative procedure than that given in the JTP, to ensure that it was non-explosive in an oxygen-rich environment. This testing passed; however, a mixture of solvent and surfactant (not required by the JTP) was found to be reactive during testing. This testing indicated that care must be taken to ensure that all traces of the surfactant, when used, are removed prior to reintroduction to service.

Material compatibility test was completed on only those materials where actual oxygen line components could be used as samples. This was done to ensure validity of results. Because only actual oxygen line components were used, some materials listed in the JTP were not tested. The test procedure was performed three times to simulate three lifetime PDM refurbishing cycles. All tested samples met the acceptance criterion that there be no visible or permanent evidence of substrate deterioration. However, two of the samples, both silicone rubber, had a considerable weight loss during (5%-13%) during testing and it is recommended that this material be further evaluated to ensure there is no material deterioration. GC testing was inconclusive.

Nonvolatile testing was conducted in order to provide a qualitative determination of how well the oxygen lines were cleaned by using a relative comparison of the NVR weights before and after cleaning. As noted above, there were problems associated with

performing the tests suggested in the JTP (ASTM F331) using the OLCS; therefore, a different test method was devised. The results are given in this JTR, however because of the different test method, they cannot be compared to the JTP acceptance criteria.

For the cleanliness testing, contaminant samples were weighed before and after cleaning and from this a % clean calculated. The % clean ranged from 84.62% to 100%. However, since no  $\pm$  wt% acceptance criterion was provided in the JTP or ASTM G127-95 for this test, it cannot be stated that the samples passed or failed the cleanliness testing.

Functional testing indicated no problems associated with use. Government representative observed, and approved the use of this equipment on the B-1B, F-15, F-16, and C-130 aircraft. Dead area testing indicated that the dry air purge of the system must be used in conjunction with the vacuum purge to assure that no HFE-7100 remains in the aircraft after the cleaning procedure. The leak testing conducted as part of the OLCS procedure is a high-pressure test for determining the potential loss of solvent in an aircraft; test results from the modified procedure indicated that the system passed the high-pressure test and that the solvent did not present a hazard during use.

The Component/Model/System Replica Test was conducted on the B-1B, F-15, F-16, and C-130 aircraft, the system was inspected and approved by government personnel.

A Dead Area test procedure was developed to identify redeposition areas, since the specification cited in the JTP, ASTM G88, does not provide any specific test method. Halide detection testing was conducted and after testing the dead-space was removed and visually inspected. No trace of HFE-7100 was present in the dead-space volume after evacuation.

The OLCS unit uses a high-pressure leak test to determine the potential loss of solvent in an aircraft. The average leak rate for the pressure test on the B-1 mock-up is 0.18 psi/min.

In considering the risk for fire and/or explosion when using a solvent in an oxygen rich environment, extensive testing has been performed on HFE-7100, the cleaning solvent used in the OLCS. These tests proved that HFE-7100 is non-explosive in a pure oxygen environment and is unable to sustain a fire under normal operating conditions.

Northrop Grumman submitted samples contaminated with ARD with either distilled water or Krytox grease for the off-aircraft soil removal test. This test met the JTP requirements, but the JTP lists seven contaminants for this test, none of which were tested.

Water content for off-aircraft testing was not conducted at all. Therefore, no results or conclusions about whether icing will be prevented, or about potential corrosion of oxygen systems onboard aircraft, can be made at this time.

To summarize, most of the tests listed in the JTP were conducted either as specified in the JTP or per the modification stated in this JTR. These results indicated that the technologies would be acceptable for this application. It should be noted that some of this testing was more limited in scope than stated in the JTP; the specifics of these limitations have been previously described in this report. Conclusions as to the results of some of these tests have not been made at this time, since the acceptance criteria specified in the JTR is not applicable to the revised procedures. No conclusions can be drawn about the prevention of icing or potential corrosion of the systems, since water content testing of the off-aircraft system was not conducted. The nonvolatile residue test was also not conducted on the Northrop Grumman off-aircraft system.

The information contained in this report is presented to enable potential users of these systems/solvents to decide if they are feasible for their application. These systems/solvents can potentially be utilized to clean almost any type line (hydraulic, fuel, coolant, environmental, etc.) on several different applications, such as tanks, machinery, and hospital oxygen lines.

Additional engineering and testing would be required to adapt this technology to a specific application, but the transition should not pose any problems.

## 6.0 REFERENCE DOCUMENTS

The documents listed in Table 22 were referenced in the descriptions of tests defined in this JTR (not previously defined in the JTP). References used for defining the tests contained in the JTP are included in the JTP.

**Table 22. Reference Documents for JTR Test Descriptions**

Reference Document	Title	Date	JTP Test	JTP Section	Applicable Section(s) of Reference Document
ASTM G86-98a	Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments	September 10, 1998	LOX Impact	2.1	
ASTM G72 - 82	Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment	Reapproval 1996	LOX Impact	2.1	

You can find all appendices below:

- [Appendix A](#): Cleaning Equipment Descriptions, Procedures and Photographs
- [Appendix B](#): NASA JSC Test Requests
- [Appendix C](#): Material Compatibility Procedures, Surfactant Calculation, Sample Codes, Photographs of Test Results, and Gas Chromatograph Chromatograms
- [Appendix D](#): Nonvolatile Residue Test Procedure, Test Results and Photographs
- [Appendix E](#): Cleanliness Verification Test Results and Photographs of Samples
- [Appendix F](#): Component/Model/System Replica Test: Test/Demo and Lab Reports, Photographs of Equipment
- [Appendix G](#): Dead Areas Test Procedures and Test Data
- [Appendix H](#): Leak Testing Procedure and Test Data

- [Appendix I](#): Soil Removal: Photographs Test Jig, and Test Samples
- [Appendix J](#): Particle Count Test Report

**Appendix B**  
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**Appendix C**  
**Data Archiving and Demonstrations Plan(s)**

1. All archived data for this project will be recorded and stored at two locations, Versar Inc. offices and at Tinker OC-ALC/LGERC, AFB Oklahoma. Data will be archived on computer hard drives and/or Compact Disks (CD's). Providing that this project successfully transitions and is implemented, the Oklahoma City office will remain open and all archived data will remain at:

Versar Inc  
5717 E I-240 Service Road (Suite "B")  
Oklahoma City, OK 73135  
Phone 405-739-0062

In the event the project does not transition into use, all data will be archived at Versar headquarters in Springfield, Virginia.

Versar Inc.  
6850 Versar Center  
Springfield, VA 22151

The data will also be archived at the project manager's office at Tinker AFB, OK.

OC-ALC/LGERC  
3001 Staff Dr. Ste 1AC496A  
Tinker AFB, OK 73145-3029

2. Various project information will be stored and accessible on government web sites. Full project information for the Joint Group on Pollution Prevention (JGPP) will be stored at [www.jgpp.com](http://www.jgpp.com). This site will contain all project reports such as the JTP, and JTR.
3. To obtain copies of the approved demonstration plan, please contact either archiving location listed above, or visit the ESTCP web site at [www.estcp.org](http://www.estcp.org).

**Appendix D**  
**No Flow Testing Results / High Flow Test Results**

**DRAFT**

No Flow Testing							
		Test Coupon Weight (grams)					
			Contaminated Coupons				
		Before	Before	After	After	Cleaning	%
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned
	<b>WD 40 &amp; ARD</b>	2.1718	2.2510	2.2253	2.2247	30 Sec	1.12%
HFE 7100	WD 40 & ARD	2.0733	2.1366	2.1204	2.1197	1 Min	1.49%
Only	WD 40 & ARD	2.2230	2.3255	2.2948	2.2935	2 Min	1.81%
	WD 40 & ARD	2.3014	2.3908	2.3620	2.3599	5 Min	3.47%
	WD 40 & ARD	2.0786	2.1566	2.1286	2.1276	30 Sec	2.00%
HFE 7100 &	WD 40 & ARD	2.3131	2.4187	2.3816	2.3802	1 Min	2.04%
Krytox Alc.	WD 40 & ARD	2.1481	2.2379	2.2104	2.2089	2 Min	2.41%
	WD 40 & ARD	2.1088	2.1822	2.1608	2.1581	5 Min	5.19%
	WD 40 & ARD	2.1168	2.2070	2.1812	2.1486	30 Sec	50.62%
AK-225G	WD 40 & ARD	1.1808	1.8913	1.8724	1.8192	1 Min	7.69%
	WD 40 & ARD	2.3272	2.4261	2.4016	2.3426	2 Min	79.30%
	WD 40 & ARD	1.7278	1.7998	1.7833	1.7376	5 Min	82.34%
	WD 40 & ARD	2.1718	2.1216	2.2008	2.2003	30 Sec	1.72%
HFE 7100 &	WD 40 & ARD	2.0733	2.2084	2.1087	2.1078	1 Min	2.54%
Krytox Alc.	WD 40 & ARD	2.2330	2.3566	2.3029	2.3018	2 Min	1.57%
(repeat)	WD 40 & ARD	2.3014	2.3793	2.3508	2.3489	5 Min	3.85%
	WD 40 & ARD	2.0786	2.1499	2.1243	2.1154	30 Sec	19.47%
AK-225G	WD 40 & ARD	2.3131	2.3915	2.3681	2.3341	1 Min	61.82%
(repeat)	WD 40 & ARD	2.1481	2.2674	2.248	2.1511	2 Min	97.00%
	WD 40 & ARD	2.1088	2.1828	2.1658	2.1177	5 Min	84.39%

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
		Before	Before	After	After	Cleaning	%	
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned	
	<b>MS139 &amp; ARD</b>	2.1718	2.3038	2.2776	2.2234	30 Sec	51.23%	
HFE 7100	MS139 & ARD	2.0733	2.1781	2.1394	2.1202	1 Min	29.05%	
Only	MS139 & ARD	2.2230	2.3677	2.3382	2.3411	2 Min	-2.52%	
	MS139 & ARD	2.3014	2.4376	2.4012	2.3448	5 Min	56.51%	
	MS139 & ARD	2.0786	2.1732	2.1534	2.1230	30 Sec	40.64%	
HFE 7100 &	MS139 & ARD	2.3131	2.4694	2.4388	2.3692	1 Min	55.37%	
Krytox Alc.	MS139 & ARD	2.1481	2.3009	2.2751	2.2092	2 Min	51.89%	
	MS139 & ARD	2.1088	2.2446	2.2190	2.1850	5 Min	30.85%	
	MS139 & ARD	2.1168	2.1915	2.1732	2.1729	30 Sec	0.53%	
AK-225G	MS139 & ARD	1.1808	1.9009	1.8835	1.8551	1 Min	4.04%	
	MS139 & ARD	2.3272	2.4562	2.4340	2.4354	2 Min	-1.31%	
	MS139 & ARD	1.7278	1.8275	1.8085	1.7987	5 Min	12.14%	
	<b>MIL 7808 &amp; ARD</b>	2.1718	2.2462	2.2460	2.2415	30 Sec	6.06%	
HFE 7100	MIL 7808 & ARD	2.0733	2.1604	2.1604	2.1523	1 Min	9.30%	
Only	MIL 7808 & ARD	2.2230	2.2944	2.2944	2.2853	2 Min	12.75%	
	MIL 7808 & ARD	2.3014	2.3812	2.3780	2.3569	5 Min	27.55%	

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
		Before	Before	After	After	Cleaning	%	
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned	
	MIL 7808 & ARD	2.0786	2.1601	2.1598	2.1558	30 Sec	4.93%	
HFE 7100 &	MIL 7808 & ARD	2.3131	2.3804	2.3801	2.3728	1 Min	10.90%	
Krytox Alc.	MIL 7808 & ARD	2.1481	2.2072	2.2070	2.1965	2 Min	17.83%	
	MIL 7808 & ARD	2.1088	2.1735	2.1733	2.1553	5 Min	27.91%	
	MIL 7808 & ARD	2.1168	2.1882	2.1878	2.1628	30 Sec	35.21%	
AK-225G	MIL 7808 & ARD	1.1808	1.8920	1.8916	1.8787	1 Min	1.81%	
	MIL 7808 & ARD	2.3272	2.3922	2.3917	2.3431	2 Min	75.35%	
	MIL 7808 & ARD	1.7278	1.8075	1.8071	1.7567	5 Min	63.56%	
	<b>MIL 5606 &amp; ARD</b>	2.1718	2.3021	2.2321	2.2276	30 Sec	7.46%	
HFE 7100	MIL 5606 & ARD	2.0733	2.1480	2.1430	2.1051	1 Min	54.38%	
Only	MIL 5606 & ARD	2.2230	2.2465	2.2878	2.2825	2 Min	8.18%	
	MIL 5606 & ARD	2.3014	2.3858	2.3730	2.3418	5 Min	43.58%	
	MIL 5606 & ARD	2.0786	2.1399	2.1277	2.1225	30 Sec	10.59%	
HFE 7100 &	MIL 5606 & ARD	2.3131	2.3851	2.3769	2.3498	1 Min	42.48%	
Krytox Alc.	MIL 5606 & ARD	2.1481	2.2038	2.1967	2.1831	2 Min	27.98%	
	MIL 5606 & ARD	2.1088	2.1762	2.1691	2.1483	5 Min	34.49%	
	MIL 5606 & ARD	2.1168	2.1684	2.1598	2.1260	30 Sec	78.60%	

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
		Before	Before	After	After	Cleaning	%	
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned	
AK-225G	MIL 5606 & ARD	1.1808	1.8677	1.8599	1.8128	1 Min	6.94%	
	MIL 5606 & ARD	2.3272	2.4180	2.4087	2.3280	2 Min	99.02%	
	MIL 5606 & ARD	1.7278	1.8043	1.7954	1.7281	5 Min	99.56%	
	<b>Amberlube &amp; ARD</b>	2.1718	2.2942	2.2907	2.2899	30 Sec	0.67%	
HFE 7100	Amberlube & ARD	2.0733	2.3443	2.3406	2.3400	1 Min	0.22%	
Only	Amberlube & ARD	2.2230	2.2669	2.2642	2.2634	2 Min	1.94%	
	Amberlube & ARD	2.3014	2.4110	2.4076	2.4066	5 Min	0.94%	
	Amberlube & ARD	2.0786	2.1840	2.1812	2.1796	30 Sec	1.56%	
HFE 7100 &	Amberlube & ARD	2.3131	2.4002	2.3980	2.3967	1 Min	1.53%	
Krytox Alc.	Amberlube & ARD	2.1481	2.2639	2.2606	2.2588	2 Min	1.60%	
	Amberlube & ARD	2.1088	2.2260	2.2227	2.2208	5 Min	1.67%	
	Amberlube & ARD	2.1168	2.2281	2.2245	2.2190	30 Sec	5.11%	
AK-225G	Amberlube & ARD	1.1808	1.9186	1.9150	1.9037	1 Min	1.54%	
	Amberlube & ARD	2.3272	2.4367	2.4330	2.4081	2 Min	23.53%	
	Amberlube & ARD	1.7278	1.8107	1.8086	1.7616	5 Min	58.17%	
	<b>25i Blue Wave &amp; ARD</b>	2.1718	2.2086	2.2016	2.2019	30 Sec	-1.01%	*
HFE 7100	25i Blue Wave & ARD	2.0733	2.1124	2.1033	2.1037	1 Min	-1.33%	*
Only	25i Blue Wave & ARD	2.2230	2.2903	2.2756	2.2760	2 Min	-0.76%	*
	25i Blue Wave & ARD	2.3014	2.3428	2.3301	2.3305	5 Min	-1.39%	*

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
	CONTAMINANT	Before Contamination	Before Drying	After Drying	After Cleaning	Cleaning Time	% Cleaned	
	25i Blue Wave & ARD	2.0786	2.1315	2.1106	2.1108	30 Sec	-0.62%	*
HFE 7100 &	25i Blue Wave & ARD	2.3131	2.3654	2.3493	2.3497	1 Min	-1.10%	*
Krytox Alc.	25i Blue Wave & ARD	2.1481	2.1901	2.1764	2.1766	2 Min	-0.71%	*
	25i Blue Wave & ARD	2.1088	2.1500	2.1382	2.1384	5 Min	-0.68%	*
	25i Blue Wave & ARD	2.1168	2.1473	2.1439	2.1407	30 Sec	11.81%	
AK-225G	25i Blue Wave & ARD	1.1808	1.8532	1.8532	1.8437	1 Min	1.41%	
	25i Blue Wave & ARD	2.3272	2.3673	2.3591	2.3507	2 Min	26.33%	
	25i Blue Wave & ARD	1.7278	1.7653	1.7551	1.7423	5 Min	46.89%	
						Unexplained		
	<b>Krytox Alcohol &amp; ARD</b>	2.1718	2.2571	2.2552	2.1728	30 Sec	98.80%	
HFE 7100	Krytox Alcohol & ARD	2.0733	2.1679	2.1634	2.0736	1 Min	99.67%	
Only	Krytox Alcohol & ARD	2.2230	2.3188	2.3168	2.2337	2 Min	88.59%	
	Krytox Alcohol & ARD	2.3014	2.3774	2.3760	2.3021	5 Min	99.06%	
	Krytox Alcohol & ARD	2.0786	2.1550	2.1314	2.0796	30 Sec	98.11%	
HFE 7100 &	Krytox Alcohol & ARD	2.3131	2.4104	2.4010	2.3136	1 Min	99.43%	
Krytox Alc.	Krytox Alcohol & ARD	2.1481	2.2371	2.2104	2.1483	2 Min	99.68%	
	Krytox Alcohol & ARD	2.1088	2.2132	2.1910	2.1091	5 Min	99.64%	

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
		Before	Before	After	After	Cleaning	%	
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned	
	Krytox Alcohol & ARD	2.1168	2.1942	2.1924	2.1208	30 Sec	94.71%	
AK-225G	Krytox Alcohol & ARD	1.1808	1.8980	1.8900	1.8114	1 Min	11.08%	
	Krytox Alcohol & ARD	2.3272	2.4292	2.4276	2.3277	2 Min	99.50%	
	Krytox Alcohol & ARD	1.7278	1.8116	1.8107	1.7280	5 Min	99.76%	
	Krytox Grease & ARD	2.1718	2.3915	2.3911	2.3808	30 Sec	4.70%	
HFE 7100	Krytox Grease & ARD	2.0733	2.2474	2.2472	2.2332	1 Min	8.05%	
Only	Krytox Grease & ARD	2.2230	2.4894	2.4891	2.4574	2 Min	11.91%	
	Krytox Grease & ARD	2.3014	2.5622	2.5592	2.4851	5 Min	28.74%	
	Krytox Grease & ARD	2.0786	2.2913	2.2912	2.2808	30 Sec	4.89%	
HFE 7100 &	Krytox Grease & ARD	2.3131	2.6224	2.6224	2.5933	1 Min	9.41%	
Krytox Alc.	Krytox Grease & ARD	2.1481	2.3644	2.3642	2.3474	2 Min	7.77%	
	Krytox Grease & ARD	2.1088	2.3112	2.3091	2.2581	5 Min	25.46%	
	Krytox Grease & ARD	2.1168	2.3090	2.3089	2.2979	30 Sec	5.73%	
AK-225G	Krytox Grease & ARD	1.1808	2.0234	2.0233	2.0089	1 Min	1.71%	
	Krytox Grease & ARD	2.3272	2.5827	2.5824	2.5565	2 Min	10.15%	
	Krytox Grease & ARD	1.7278	1.9195	1.9194	1.8890	5 Min	15.87%	
	<b>Hydrocarbon Grease &amp; ARD</b>	2.1718	2.2355	2.2351	2.2345	30 Sec	0.95%	
HFE 7100	Hydrocarbon Grease &	2.0733	2.1466	2.1466	2.1459	1 Min	0.95%	

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
	CONTAMINANT	Before Contamination	Before Drying	After Drying	After Cleaning	Cleaning Time	% Cleaned	
	ARD							
Only	Hydrocarbon Grease & ARD	2.2230	2.3091	2.3090	2.3081	2 Min	1.05%	
	Hydrocarbon Grease & ARD	2.3014	2.3897	2.3894	2.3872	5 Min	2.50%	
	Hydrocarbon Grease & ARD	2.0786	2.1327	2.1326	2.1323	30 Sec	0.56%	
HFE 7100 &	Hydrocarbon Grease & ARD	2.3131	2.3615	2.3614	2.3608	1 Min	1.24%	
Krytox Alc.	Hydrocarbon Grease & ARD	2.1481	2.1987	2.1984	2.1975	2 Min	1.79%	
	Hydrocarbon Grease & ARD	2.1088	2.1758	2.1756	2.1740	5 Min	2.40%	
	Hydrocarbon Grease & ARD	2.1168	2.1876	2.1868	2.1781	30 Sec	12.43%	
AK-225G	Hydrocarbon Grease & ARD	1.1808	1.8926	1.8927	1.8802	1 Min	1.76%	
	Hydrocarbon Grease & ARD	2.3272	2.4239	2.4236	2.4001	2 Min	24.38%	
	Hydrocarbon Grease & ARD	1.7278	1.8099	1.8099	1.7789	5 Min	37.76%	

No Flow Testing								
		Test Coupon Weight (grams)						
			Contaminated Coupons					
		Before	Before	After	After	Cleaning	%	
	CONTAMINANT	Contamination	Drying	Drying	Cleaning	Time	Cleaned	
	<b>Distilled Water &amp; ARD</b>	2.1718	2.2563	2.1918	2.1912	30 Sec	3.00%	
HFE 7100	Distilled Water & ARD	2.0733	2.1932	2.1092	2.1070	1 Min	6.13%	
Only	Distilled Water & ARD	2.2230	2.3414	2.2685	2.2664	2 Min	4.62%	
	Distilled Water & ARD	2.3014	2.4187	2.3509	2.3502	5 Min	1.41%	
	Distilled Water & ARD	2.0786	2.1978	2.1277	2.1212	30 Sec	13.24%	
HFE 7100 &	Distilled Water & ARD	2.3131	2.4302	2.3588	2.3578	1 Min	2.19%	
Krytox Alc.	Distilled Water & ARD	2.1481	2.2463	2.1754	2.1663	2 Min	33.33%	
	Distilled Water & ARD	2.1088	2.1921	2.1303	2.1207	5 Min	44.65%	
	Distilled Water & ARD	2.1168	2.1676	2.1400	2.1379	30 Sec	9.05%	
AK-225G	Distilled Water & ARD	1.1808	1.8625	1.8296	1.8269	1 Min	0.42%	
	Distilled Water & ARD	2.3272	2.3982	2.3471	2.3414	2 Min	28.64%	
	Distilled Water & ARD	1.7278	1.7776	1.7491	1.7458	5 Min	15.49%	

Tests with Pure HFE-7100						
	Test Coupon Weight (grams)					
		Contaminated Coupons				
	Before	Before	After	After	%	Cleaning
CONTAMINANT	Contamination	Drying	Drying	Cleaning	CLEANED	Time
<b>WD-40</b>	3.2174	3.2412	3.2235	3.2228	11.48%	30 Sec
WD-40	3.2461	3.2694	3.2523	3.2516	11.29%	1 Min
WD-40	3.1652	3.1892	3.1715	3.1707	12.70%	2 Min
WD-40	3.0581	3.0865	3.0650	3.0642	11.59%	5 Min
WD-40	3.0156	3.037	3.0219	3.0211	12.70%	30 Sec
WD-40	2.8725	2.8919	2.8785	2.8775	16.67%	1 Min
WD-40	3.2749	3.2935	3.2804	3.2790	25.45%	2 Min
WD-40	2.9545	2.9719	2.9599	2.9582	31.48%	5 Min
<b>MIL-PRF-7808</b>	3.2174	3.2456	3.2453	3.2325	45.88%	30 Sec
MIL-PRF-7808	3.2461	3.2698	3.2695	3.2553	60.68%	1 Min
MIL-PRF-7808	3.1652	3.1872	3.1870	3.1694	80.73%	2 Min
MIL-PRF-7808	3.0581	3.0893	3.0889	3.0612	89.94%	5 Min
MIL-PRF-7808	3.0156	3.0403	3.0401	3.0319	33.47%	30 Sec
MIL-PRF-7808	2.8725	2.8981	2.8981	2.8820	62.89%	1 Min
MIL-PRF-7808	3.2749	3.2821	3.3030	3.2821	74.38%	2 Min
MIL-PRF-7808	2.9545	2.9553	2.9751	2.9555	95.15%	5 Min

Tests with Pure HFE-7100						
	Test Coupon Weight (grams)					
		Contaminated Coupons				
	Before	Before	After	After	%	Cleaning
CONTAMINANT	Contamination	Drying	Drying	Cleaning	CLEANED	Time
MIL-H-5606	3.2174	3.2599	3.2457	3.2400	20.14%	30 Sec
MIL-H-5606	3.2461	3.2970	3.2812	3.2698	32.48%	1 Min
MIL-H-5606	3.1652	3.1973	3.1854	3.1761	46.04%	2 Min
MIL-H-5606	3.0581	3.0958	3.0841	3.0640	77.31%	5 Min
MIL-H-5606	3.0156	3.0418	3.0333	3.0285	27.12%	30 Sec
MIL-H-5606	2.8725	2.9001	2.8915	2.8840	39.47%	1 Min
MIL-H-5606	3.2749	3.306	3.2967	3.2861	48.62%	2 Min
MIL-H-5606	2.9545	2.9937	2.9812	2.9611	75.28%	5 Min
Amberlube	3.2174	3.2840	3.2809	3.2812	-0.47%	30 Sec
Amberlube	3.2461	3.3503	3.3453	3.3446	0.71%	1 Min
Amberlube	3.1652	3.2488	3.2447	3.2447	0.00%	2 Min
Amberlube	3.0581	3.1216	3.1192	3.1188	0.65%	5 Min
Amberlube	3.0156	3.1260	3.1204	3.1203	0.10%	
Amberlube	2.8725	2.9585	2.9516	2.9512	0.51%	
Amberlube	3.2749	3.3303	3.3186	3.3184	0.46%	
Amberlube	2.9545	3.0340	3.0303	3.0299	0.53%	
25 I	3.2174	3.2592	3.2296	3.2295	0.82%	30 Sec

Tests with Pure HFE-7100						
	Test Coupon Weight (grams)					
		Contaminated Coupons				
	Before	Before	After	After	%	Cleaning
CONTAMINANT	Contamination	Drying	Drying	Cleaning	CLEANED	Time
25 I	3.2461	3.2739	3.2549	3.2548	1.14%	1 Min
25 I	3.1652	3.1863	3.1724	3.1723	1.39%	2 Min
25 I	3.0581	3.0831	3.0667	3.0666	1.16%	5 Min
25 I	3.0156	3.052	3.0270	3.0269	0.88%	30 Sec
25 I	2.8725	2.8932	2.8806	2.8805	1.23%	1 Min
25 I	3.2749	3.2955	3.2835	3.2834	1.16%	2 Min
25 I	2.9545	2.9814	2.9656	2.9655	0.90%	5 Min
<b>Krytox Alcohol</b>	3.2174	3.3212	3.3020	3.2182	99.05%	30 Sec
Krytox Alcohol	3.2461	3.3225	3.3143	3.2461	100.00%	1 Min
Krytox Alcohol	3.1652	3.2162	3.2052	3.1652	100.00%	2 Min
Krytox Alcohol	3.0581	3.1212	3.1026	3.0581	100.00%	5 Min
Krytox Alcohol	3.0156	3.0807	3.0700	3.0176	96.32%	30 Sec
Krytox Alcohol	2.8725	2.9659	2.9186	2.8726	99.78%	1 Min
Krytox Alcohol	3.2749	3.3834	3.3524	3.2749	100.00%	2 Min
Krytox Alcohol	2.9545	3.0587	3.0229	2.9545	100.00%	5 Min
<b>Krytox Alcohol</b>	3.2174	3.2600	3.2573	3.2179	98.75%	30 Sec
Krytox Alcohol	3.2461	3.2972	3.2950	3.2462	99.80%	1 Min
Krytox Alcohol	3.1652	3.2012	3.1972	3.1653	99.69%	2 Min
Krytox Alcohol	3.0581	3.1001	3.0981	3.0581	100.00%	5 Min

Tests with Pure HFE-7100						
	Test Coupon Weight (grams)					
		Contaminated Coupons				
	Before	Before	After	After	%	Cleaning
CONTAMINANT	Contamination	Drying	Drying	Cleaning	CLEANED	Time
Krytox Alcohol	3.0156	3.0698	3.0682	3.0161	99.05%	30 Sec
Krytox Alcohol	2.8725	2.9127	2.9112	2.8728	99.22%	1 Min
Krytox Alcohol	3.2749	3.3312	3.3243	3.2757	98.38%	2 Min
Krytox Alcohol	2.9545	2.9945	2.9945	2.9551	98.50%	5 Min

## HIGH FLOW TEST RESULTS FOR AK-225G TESTING

3/8" test cells were utilized for this testing. The solvent was pumped through a line system using a pump with up to five (5) gpm flow capacity. Each test was conducted by circulating the fluid through the lines and the 3/8" test cell for a period of five (5) minutes.

The test cells were contaminated with the various NVR contaminants mixed with Arizona Road Dust. They were weighed before contamination, contaminated and photographed, weighed with the contamination, and dried in a scientific oven for a period of thirty (30) minutes. The cells were then removed from the oven, allowed to dry for a period of fifteen (15) minutes, weighed once again, photographed, and then placed in the test cell clamping device. The cell was then placed in the lines from the OLCS and cleaned as described in the above paragraphs. The same procedures were followed for all tests, utilizing the following contaminants:

- 1.) WD-40 (Lubricant) and Arizona Road Dust
- 2.) MIL-PRF-7808 (Hydraulic Fluid) and Arizona Road Dust
- 3.) MIL-C-5606 (Hydraulic Fluid) and Arizona Road Dust
- 4.) Distilled Water and Arizona Road Dust
- 5.) MS139A (Coolant) and Arizona Road Dust
- 6.) 25i (Detergent) and Arizona Road Dust
- 7.) Amberlube (Tube Bending Lube) and Arizona Road Dust
- 8.) Krytox Grease and Arizona Road Dust
- 9.) Hydrocarbon Grease and Arizona Road Dust

After the cleaning process, the test cells were allowed to air-dry for a period of ten (10) minutes. They were again photographed and weighed, and the test results were recorded on a spreadsheet.

The AK-225G appeared to be a much more aggressive solvent, in that it cleaned better than the HFE-7100 in most instances. Testing under the same velocity as that utilized with the HFE-7100 was not conducted due to the limitations of the pump used for AK-225G testing. Utilizing the same pump used for HFE-7100 testing would have necessitated cleaning the entire OLCS system, adding the AK-225G, performing the required tests and then cleaning the unit again. This was not considered to be practical, given the high cleaning rates observed during the initial test results. Obviously, had the same solvent flow velocities been attained, the AK-225G would have approached the 100% cleanliness level in all instances.

As stated previously, the AK-225G is more aggressive; however, there is a definite, very pungent odor associated with the solvent. Should this solvent be utilized in an actual aircraft cleaning and demonstration, further testing would be required to prove compatibility, and to ensure that all odors would be completely removed from the system.

Attached are the results of the tests compared with those performed with HFE-7100.

**HIGH-FLOW   NVR TESTS   3/8" LINES   AK-225G**

<b>Contaminant</b>	<b>Initial (Clean)</b>	<b>Coupon Weight (grams)</b>		<b>After Cleaning</b>	<b>% Clean AK-225G</b>	<b>% Clean W/HFE-7100</b>	
		<b>Before Drying</b>	<b>After Drying</b>				
WD-40 & ARD	0.4965	0.5621	0.5508	0.4965	100.00%	99.29%	
MIL 7808 & ARD	0.5195	0.5937	0.5928	0.5197	99.73%	99.82%	
Mil 5606 & ARD	0.4977	0.5384	0.5344	0.4978	99.73%	83.69%	(Avg.)
Dist Water & ARD	0.4965	0.6209	0.5593	0.4965	100.00%	98.58%	
MS 139A & ARD	0.5195	0.6274	0.6064	0.5195	100.00%	98.40%	
25i Blue Wave & ARD	0.4977	0.5875	0.5539	0.4979	99.64%	95.94%	
Amberlube & ARD	0.5129	0.6304	0.6273	0.5129	100.00%	97.82%	
Krytox GR. & ARD	0.5195	0.6553	0.6551	0.5195	100.00%	99.90%	
Hydrocarbon GR & ARD	0.4977	0.5885	0.5877	0.4977	100.00%	N/A	

**Note 1:** Testing with AK225G conducted with small red pump capable of up to 5 gpm--wash time total 5 minutes.

**Note 2:** Testing with HFE 7100 conducted with large pump on OLCS capable of up to 35 gpm--wash 4 minutes, rinse

## **Appendix E**

### **Acronym and Abbreviation List**

## ACRONYM LIST

AFB	Air Force Base
ALC	Air Logistics Command
ACC	Air Combat Command
ANG	Air National Guard
ASTM	American Society for Testing and Materials
B-1B	United States Air Force Bomber Aircraft
CFC	Chlorofluorocarbons
<i>CTC</i>	Concurrent Technologies Corporation
CONUS	Continental United States
DCMC	Defense Contract Management Command
DoD	Department of Defense
DUSD-ES	Office of the Deputy Under Secretary of Defense – Environmental Security
DR	Discrepancy Report
EHS	Environmental, Health and Safety
EPA	Environmental Protection Agency
ESOH	Environmental, Safety, and Occupational Health
ESTCP	Environmental Security Technology Certification Program
GA	Georgia
GOX	Gaseous Oxygen
HCFC	Hydrochlorofluorocarbon
JG-PP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
JTR	Joint Test Report
KY	Kentucky
LIN	Liquid Nitrogen
LOX	Liquid Oxygen
MSOG	Molecular Sieve Oxygen Generating
MSDS	Materials Safety Data Sheet
NASA	National Aeronautics and Space Administration
NVR	Non-volatile Residue
O <sub>2</sub>	Oxygen
OCONUS	Outside Continental United States
ODP	Oxygen-Depleting Potential
ODS	Ozone Depleting Substance
OK	Oklahoma
OLCS	Oxygen Line Cleaning System

## ACRONYM LIST

OSHA	Occupational Safety and Health Administration
PDM	Programmed Depot Maintenance
Ph.D.	Doctor of Philosophy
POLCS	Prototype Oxygen Line Cleaning System
QIP	Quality Inspection Procedure
SAE	Society of Automotive Engineering
SEM	Scanning Electron Microscope
SM	Single Manager
USAF	U. S. Air Force
USN	U. S. Navy
WSTF	White Sands Test Facility